AD-A194 487 LONG HAUL UNDERWATER FIBER OPTIC LINK(U) NAVAL POSTGRADUATE SCHOOL MONTEREY CA F A DENAPS MAR 88 1/1

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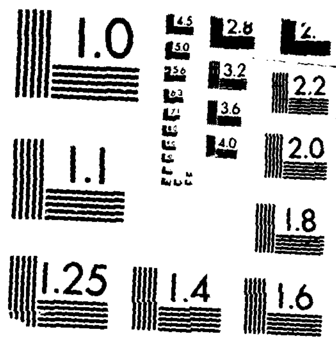

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AD-A194 487

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

LONG HAUL UNDERWATER FIBER OPTIC LINK

by

Frank A. Denap

March 1988

Thesis Advisor: J.P. Powers

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION: Naval Postgraduate School; 6b. OFFICE SYMBOL (If applicable): 62	7a. NAME OF MONITORING ORGANIZATION: Naval Postgraduate School
6c. ADDRESS (City, State, and ZIP Code): Monterey, California 93943-5000	7b. ADDRESS (City, State, and ZIP Code): Monterey, California 93943-5000
8a. NAME OF FUNDING/SPONSORING ORGANIZATION; 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)

LONG HAUL UNDERWATER FIBER OPTIC LINK

12. PERSONAL AUTHOR(S) DENAP, Frank A.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Master's Thesis	FROM ______ TO ______	1988 March	79

16. SUPPLEMENTARY NOTATION The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. government.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Fiber Optics, Optical Link

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

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20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL: J. P. POWERS	22b. TELEPHONE (Include Area Code): (408) 646-2200; 22c. OFFICE SYMBOL: 62

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE

☆ U.S. Government Printing Office: 1986—606-243

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Long Haul Underwater Fiber Optic Link

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
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This thesis presents the design, test and evaluation of a fiber optic remote monitoring system. Practical aspects of loss measurement, link analysis, receiver design, and controller implementation are examined. The fundamental operation of the system relies on conversion of the voltage data to a variable frequency TTL pulse train. The pulse train modulates a 1300 nm laser, which transmits the telemetry data via single mode fiber to the shore station. One of two test voltages can be selected by the shore-based controller, via the bidirectional link. Laboratory test results are included.

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I. INTRODUCTION

Self generating sea water batteries are currently under development for applications in long life underwater sytems. Initial performance of prototypes indicates that the output voltage depends on oxygen content and ocean currents. Long term monitoring under specified environmental conditions is required prior to fleet introduction, particularly deep water testing of battery and converter systems. To achieve test conditions and maintain design flexibility a fiber optic-based system was developed to telemeter measurement information to shore [Ref. 1]. Figure 1 illustrates the overall concept of this system. The kernel of the preliminary system was conversion of the voltage data to a variable frequency TTL pulse train. The pulse train modulated an 820 nm GaAlAs LED which transmitted light through a 50/120 micron fiber. The receiver detected the light and converted the TTL pulse train to a dc voltage; a computer-controlled recording system then recorded the voltage on disk. The system details are outlined in Reference 1. This initial design had a maximum range of 2.8 km and could only monitor a single voltage. Revised testing conditions specify a 30 km repeaterless link capable of monitoring the performance of the salt water battery and its voltage converter over a one year period. These specifications require design changes in the underwater

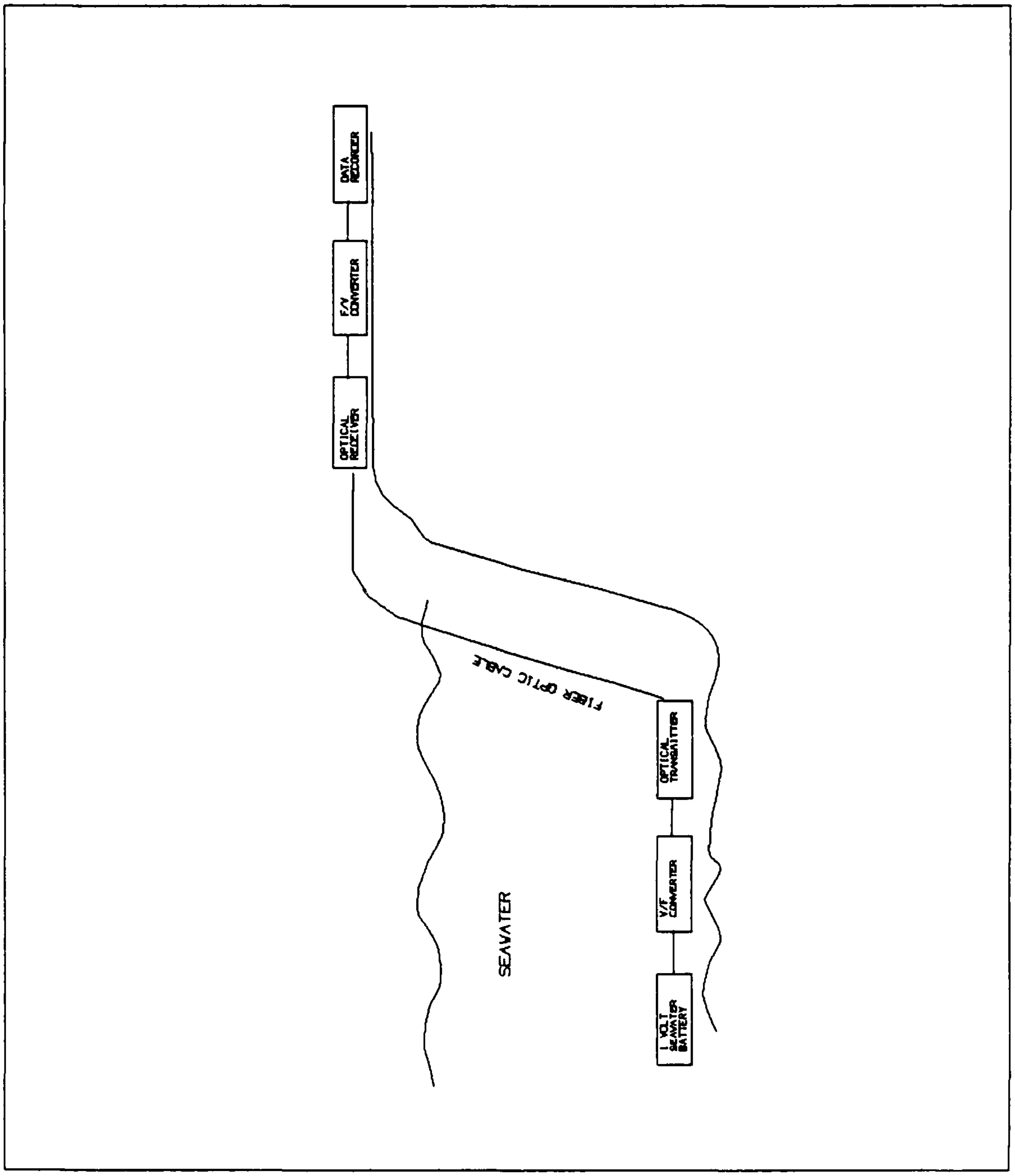

Figure 1. Preliminary System
[From Ref. 1]

and shore-based subsystems. The fundamental operation of the proposed system relies on the shore-based subassembly, which directs the underwater system to activate, select and transmit one of the two test voltages; then to receive, demodulate, sort and store the data.

This thesis will explore the practical aspects of loss measurement, link analysis, receiver design and controller implementation. Particular attention will be paid to updating the receiver module and the data collection sub-systems.

II. SYSTEM DESIGN

The revised system is illustrated in Figure 2 and includes the conversion of the original system to laser sources, bidirectional links, and controlled power and switching mechanisms. These revisions are required in order to extend the operational range to 30 km, to allow direct control of the underwater system and to conserve power. The quiescent power of the underwater subsystem is consumed by the receive module and control logic. When signalled from shore the control logic activates the laser module, the V/F converter and the data switching mechanism. The "desired" sample voltage is then selected, conditioned and used to modulate the laser source. The optical signal is transmitted with a 1300 nm laser through a bidirectional coupler over single mode fiber. If properly coupled and spliced, the fiber's reduced attenuation will support the required 30 km link.

A. CHANNEL

1. Losses

The fiber optic design process commences with the maximum tolerable system losses and the desired data rates. These two factors will dictate the type of fiber, receiver and transmitter to be used. Inherent losses due to absorption and scattering are a function of the fiber's molecular

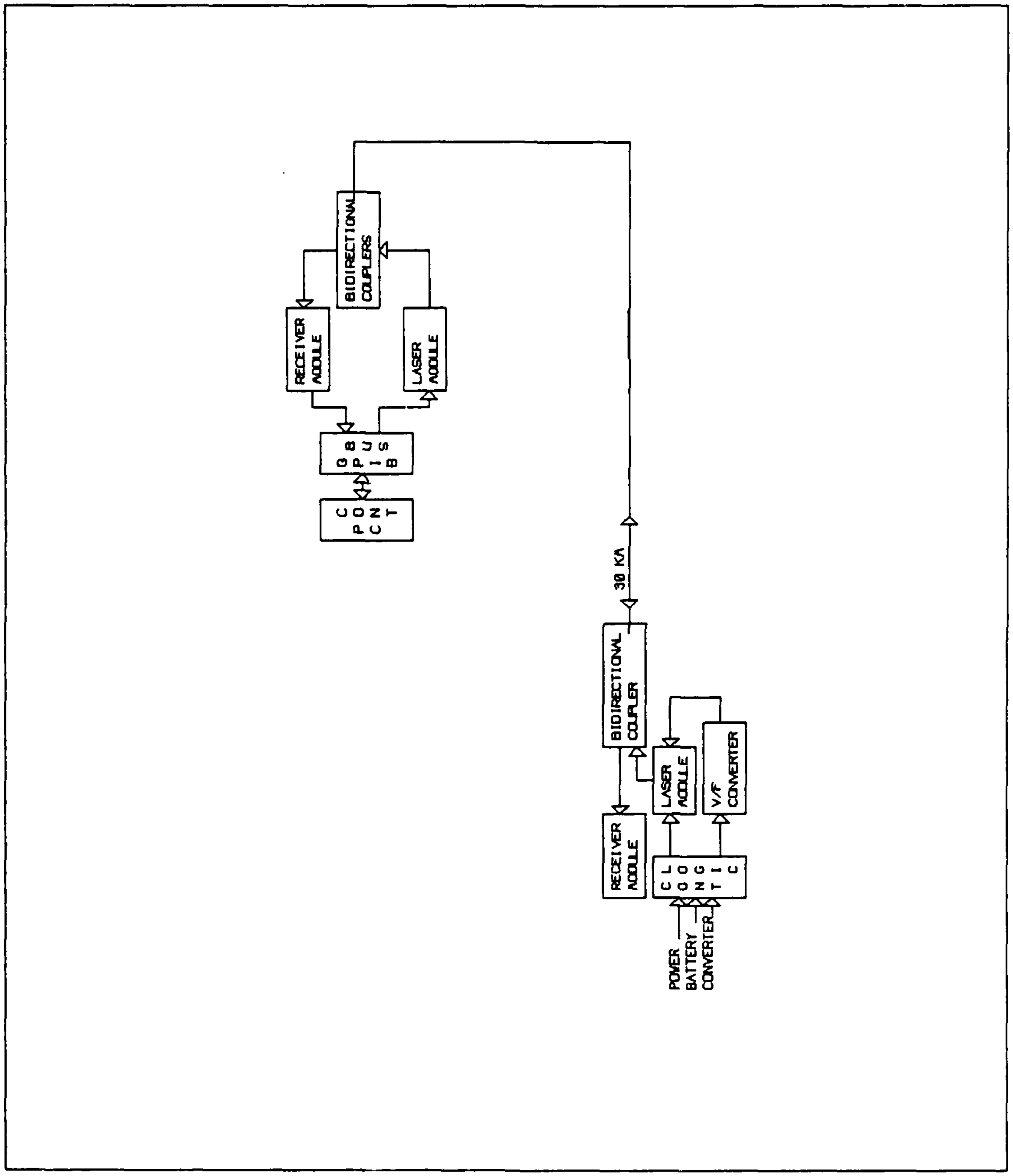

Figure 2. Revised System

composition, lattice structure and impurities [Ref. 2: pp. 73-80]. These losses are beyond the designer's control but constitute major sources of attenuation. Table 1 from Reference 3 shows some general uses for various fiber types.

The system installation losses must be minimized. Proper polishing, coupling and splicing techniques are critical with single mode fibers. These fibers have typical core diameters of 8-9 microns making them extremely susceptible to alignment losses. A variety of precision connectors are available; ST, Biconic, and FC connectors were considered, and the Biconic was chosen for this application. Biconic connectors are extremely popular, constituting approximately 60% of the long haul communication market. Their precision taper design yields a mean insertion loss of 0.5 dB and the silicon-loaded epoxy ferrule provides a thermal expansion coefficient similar to the glass fiber [Ref. 4: p. 20]. Extrinsic connecting losses are caused by:

1) longitudinal misalignment,
2) cleanliness of fiber ends,
3) angular misalignment, and
4) lateral offset (due to connector or fiber concentricity).

Biconic connectors minimize the angular and lateral misalignment, but are susceptible to increased losses due to improper fiber preparation. These connectors use spring-loaded plugs, which are butt mated through a precision

TYPE	CORE/CLAD microns	TYP BANDWIDTH (MHz-km) @850nm	TYP BANDWIDTH (MHz-km) @1300nm	LOSS (dB/km) @850nm	LOSS (dB/km) @1300nm	APPLICATION AREAS
Single-mode	9/125		10000*	2.0	0.35-0.7 (0.2-0.5@ 1550nm)	very long dist telecom
Multimode glass/glass graded-index	50/125	200-1000	350-1300	3.5-6	2.0-7.0	long-dist telcom & local networking
	62.5/125	100-500	300-600	3-6	1.2-2.0	high speed local networking & links
	85/125	100-500	800	3.5-6	1.2-2.0	
	100/140	100-400	100-300	5-7	6	local networking & links
Multimode	200/230	17	-	6		low speed links high radiation environments
glass/plastic	400/440	13	-	6		
step-index	600/650	8		6		

*assumes source linewidth of 10nm. Bandwidth can be much larger at 1550nm with narrower source linewith

Table 1. Fiber Parameters
[From Ref. 3]

alignment sleeve. When these plugs are incorrectly polished the ferrule tips may be too long and unseat the sister plug, or they may be too short and create an air gap between the plugs causing increased Fresnel losses. [Ref. 4: p 20] To ensure minimum loss, a fiber optic polisher such as those manufactured by Buehler should be used and followed by a post polishing inspection with a fiberscope. AT&T has recently introduced keyed biconic connectors, to ensure repeatable performance. Connecting losses should not be greater than 0.5 dB per connector [Ref. 4: p. 20].

An Orionics multimode fusion splicer and a Sumitomo single mode fusion splicer were used to splice the fiber when cable strength members were required to be rejoined. After stripping the fiber cable materials and fiber jacket and cleaving the fiber, the ends should be cleaned and examined. A good cleaving tool is essential if minimum losses are to be achieved. The cleaving tool scribes the fiber and stress is applied to propagate the crack. Figure 3a shows a typical poor fracture. With a good cleave, the mirror zone will extend across the fiber, and the mist and hackle zones that contribute to scattering losses will be eliminated [Ref. 5: pp. 288-295]. The hand-held cleaving instrument used in this work yielded inconsistent quality and numerous attempts were required to achieve an acceptable cleave. Figure 3b illustrates some typical poor cleaves. If any of these discrepancies exist, a new cleave should be

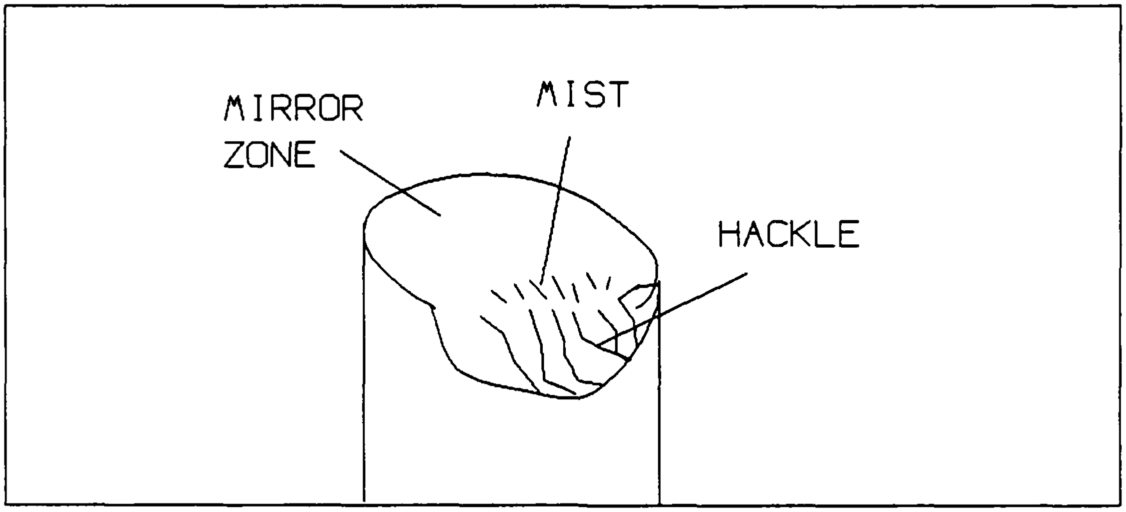

Figure 3a. Poor Fracture
[From Ref. 5]

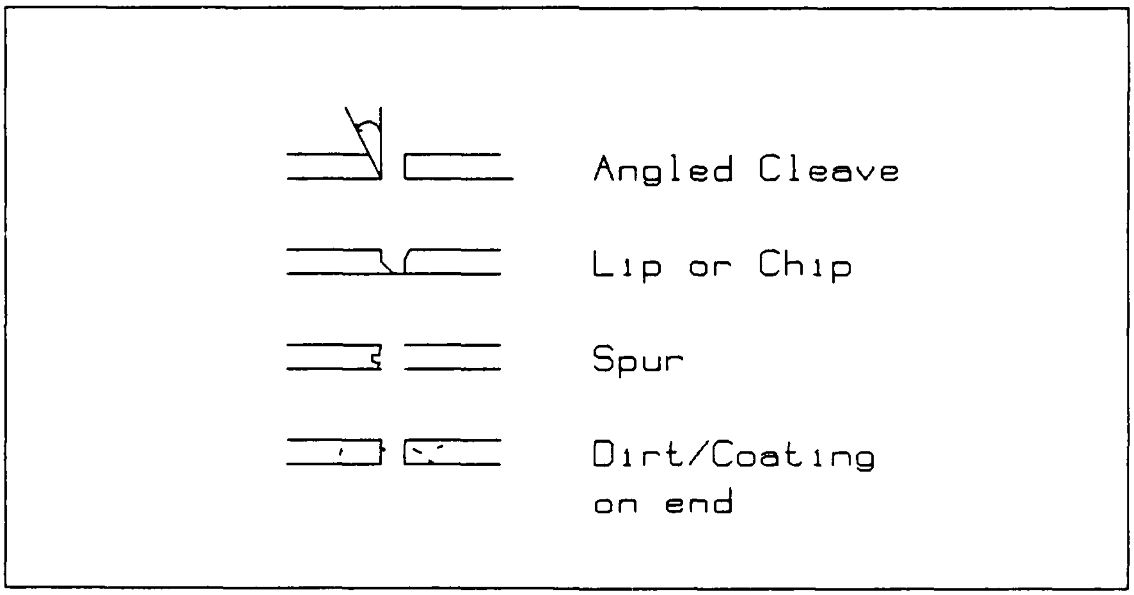

Figure 3b. Poor Cleaves

performed. Once an acceptable cleave is achieved the fiber ends are aligned (retaining a slight air gap) in the splicer using the "x y z" alignment controls. Each fiber has its own melting characteristics which influence the current level and timing adjustment. As the fiber ends start to melt, the fibers are fed slowly together. The Sumitomo has an automatic feed feature, while hand control is required on the Orionics splicer. Some typical poor splices are illustrated in Figure 4. A good splice should have no more than a 0.1 dB loss.

Specialized channel losses must be considered. In the design of the link for this thesis, bidirectional couplers were used. These couplers exhibit two types of losses, insertion loss and excess loss. Insertion loss expresses the coupling ratio; excess loss represents the power which escapes the system [Ref. 6]. Couplers produced by Gould and Aster exhibit a 3 dB insertion loss and the excess loss ranges from 1.0 to 0.08 dB depending on the cost ($99 to $795).

2. Loss Measurement

A more precise isolation of splice, connector and intrinsic fiber losses is obtained using an optical time domain reflectometer. The 10 kilometer cable of SIECOR single mode fiber (provided by NOSC of San Diego) was analyzed with a Photon Kinetics 3100 model OTDR. The 3100 model OTDR's large display and plotter output feature

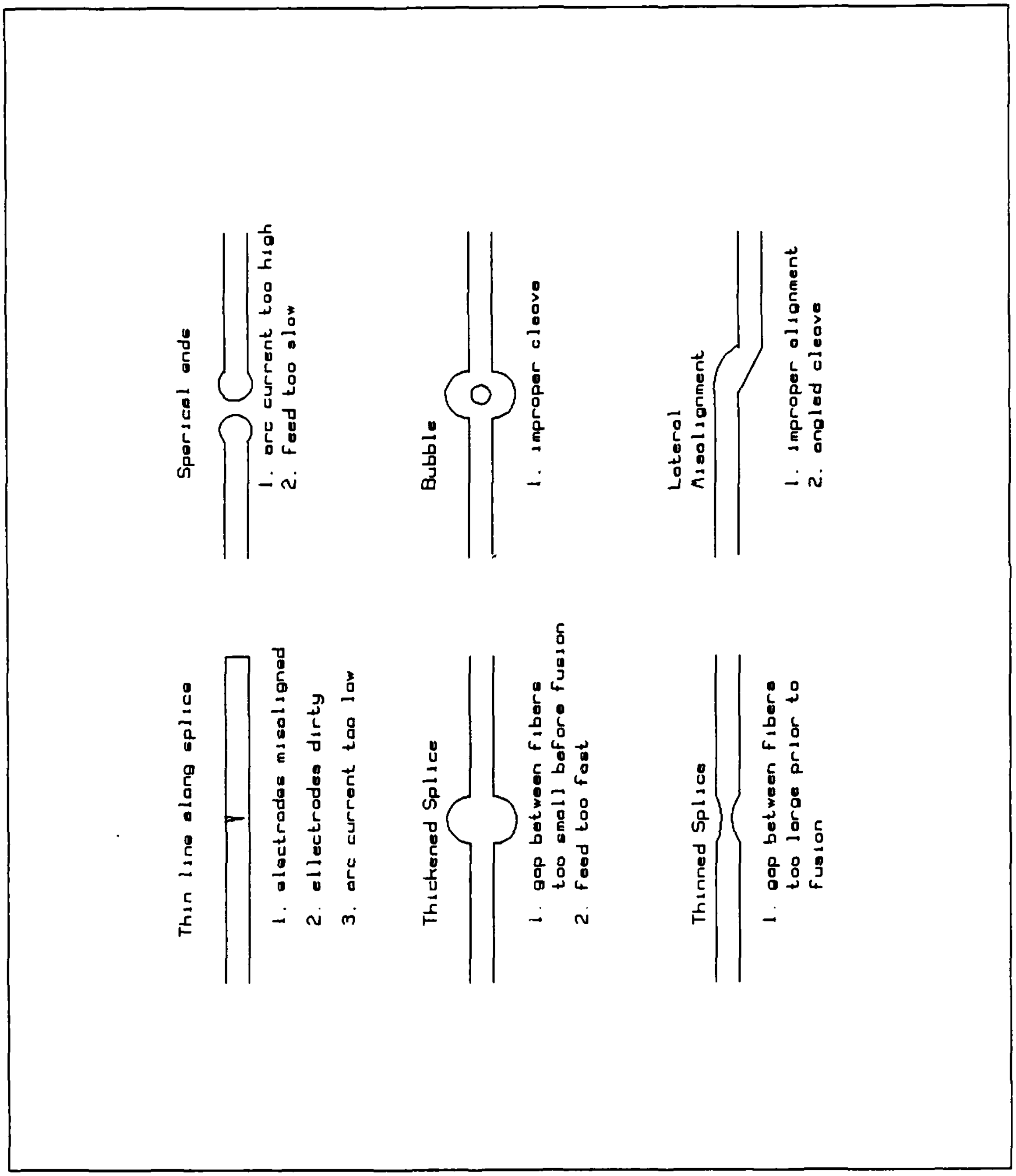

Figure 4. Typical Poor Splices

make this device easy to use, and the data was readily available. This OTDR is capable of accurately recording losses over 50 km; this capability is vital for isolating a break in long haul links. The overall fiber losses are shown in Figure 5. The initial pulse (label 1) is the signal sent by the 3100 OTDR; its shape is independent of the fiber, which is being measured. At the end of the initial pulse, a pulse recovery (label 2) occurs before the OTDR can display the backscatter light. Useful measurement information is obtained after the pulse recovery. A splice appears in the fiber signature as a drop in the backscatter light (label 3). The local area containing the splice can be examined more closely for accurate splice loss measurements. Breaks in fiber will result in a reflected pulse similar to the end reflection (label 4). Reflected pulses are caused by connectors, mechanical splices and fiber termination. Past the end reflection the OTDR will indicate the noise floor (label 5). Precise measurement near the noise floor is difficult. Accurate measurement requires that the fiber's index of refraction be entered into the OTDR. The input is displayed along with the vertical and horizontal axis labels to the right of the graphic display. The distance, total losses and losses per km between the reference bar (label 6) and cursor are displayed within the graph. Figure 6 highlights the splice loss of the region near label 3 of Figure 5. The scale has been adjusted to 1 km and 1 dB per division.

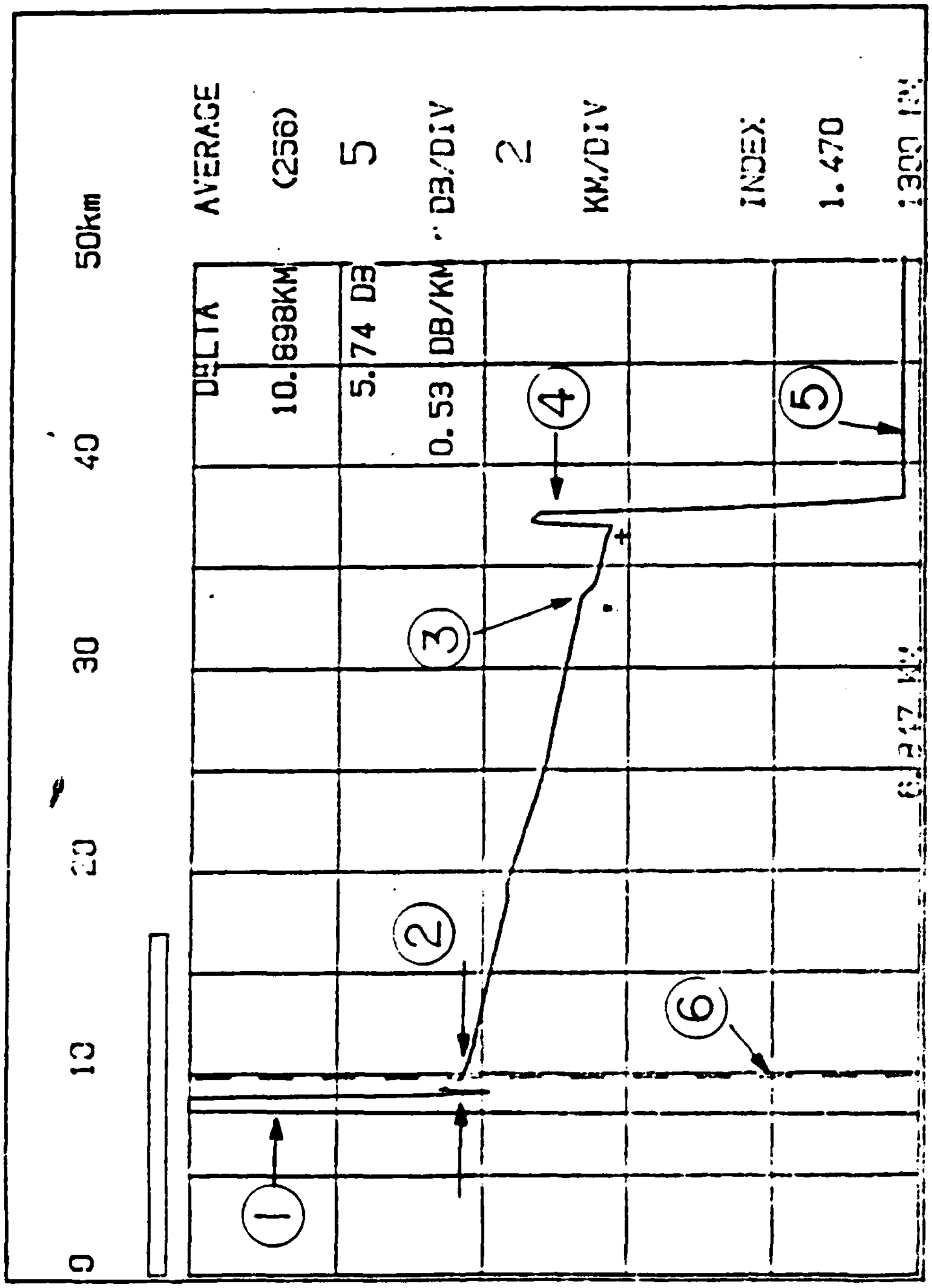

Figure 5. Overall Fiber Loss

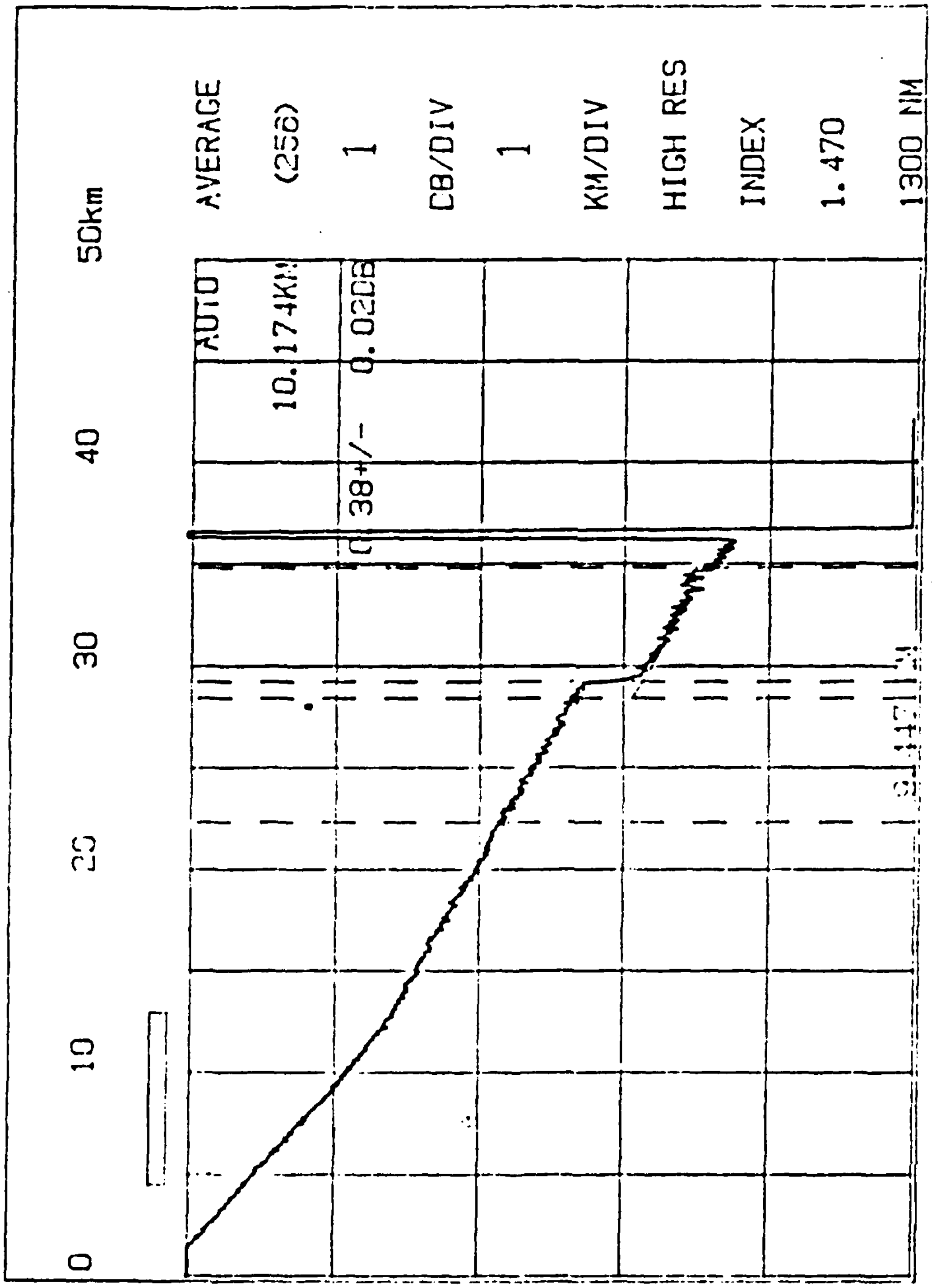

Figure 6. Splice Loss Measurement

In the "auto mode" the 3100 OTDR will automatically compute the splice loss. The splice loss and degree of accuracy are indicated in the upper right portion of Figure 6.

3. Power Budget

A power throughput analysis worksheet compares known losses and transmitted power to the required receiver sensitivity [Ref. 3: p. 60]. This worksheet, Figure 7, was completed for three different optical sources for a 30 km link. The results show that the 820 nm LED range is restricted by its low coupled power, and the high attenuation of multimode fiber. The use of single mode fiber with long wavelength devices extends the range. The 1300 nm LED is marginally usable, while the 1300 nm laser source provides 21 dB of excess power.

B. RECEIVER

The receiver design will vary with the signal format, transmitted power, and bandwidth/data rate. Digital formats, like the variable frequency TTL pulse train, simplify the design, but they require high slew rate, low noise amplifiers and comparators. A generic digital receiver consists of six main components assembled as in Figure 8.

1. Detector

The minimum detector signal level to achieve a specified bit error rate is the main criteria for detector selection. Figure 9 shows the typical minimum power versus Baud rate to achieve a bit error rate of 10^{-9} for common

	HFBR 1464 820 nm LED HFBR 2402 REC	MACOM LED LDT 60005 GO PIN-FET (REC)	LASERTRON QLM 1300 SM GO PIN-FET (REC)
AVE SOURCE COUPLED POWER	-17.5	-21 dBm	0 dBm
REC SENSITIVITY	-24.0 dBm	-53 dBm	-53 dBm
TOTAL MARGIN (P_r-P_c)	-6.5	-32	-53
FIBER LOSS (30 km)@dB/km	60 dB 2 dB/km	-15 dB 0.5 dB/km	-15 dB 0.5 dB/km
CONNECTORS	-8 dB (4 SMA)	-8 dB (2 BICONIC) (2 BIDIR.)	-8 dB (2 BICONIC) (2 BIDIR.)
ALLOWANCE FOR TIME AND TEMP DEGRADATION	-6 dB	-6 dB	-6 dB
SPLICE LOSS		-3 dB (6 SPLICE)	-3 dB (6 SPLICE)
EXCESS POWER(TM-TA)	-67.5 dB	0 dB	21 dB

Figure 7. Power Throughput Analysis Worksheet

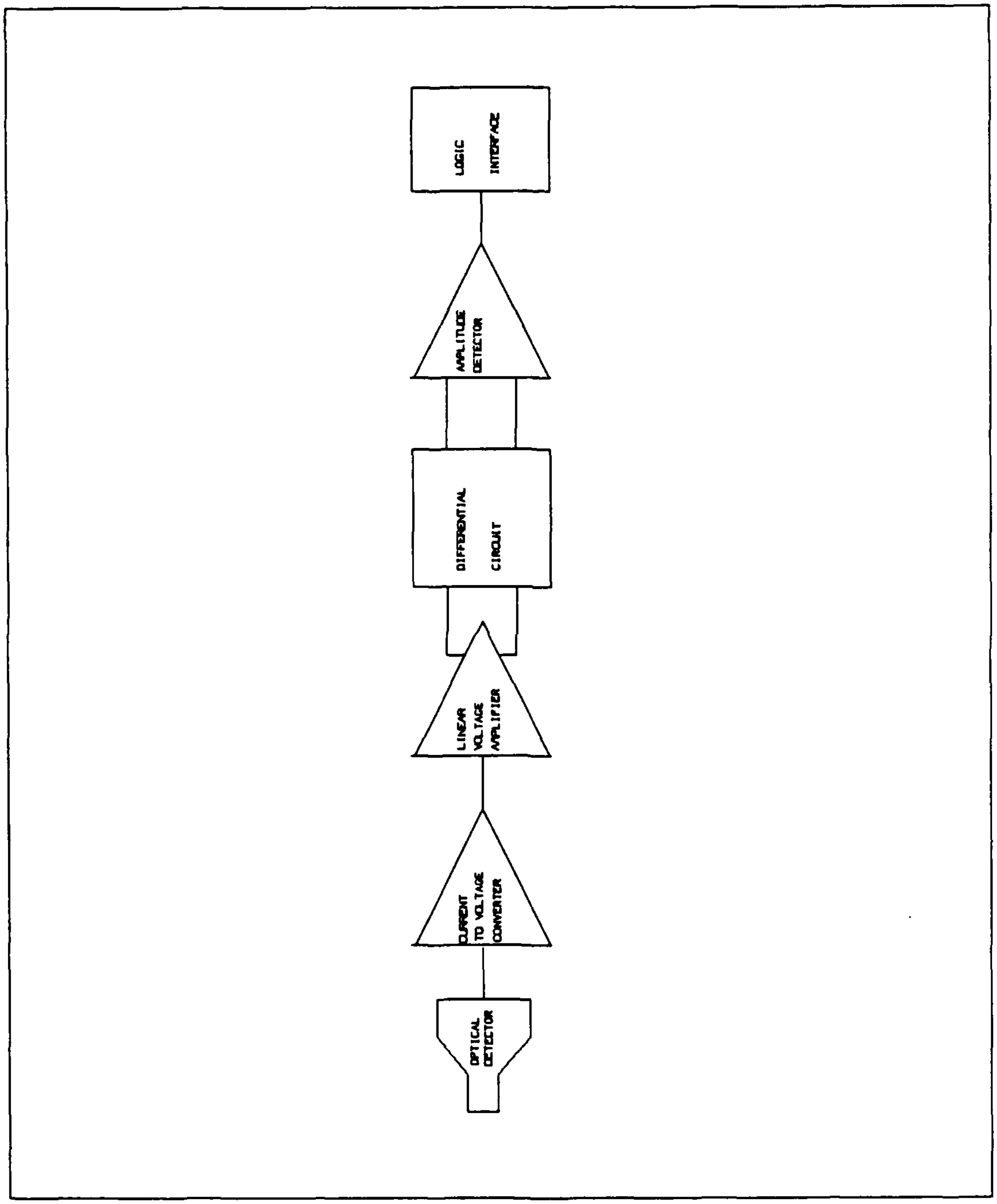

Figure 8. Overview of Digital Receiver
[From Ref. 7]

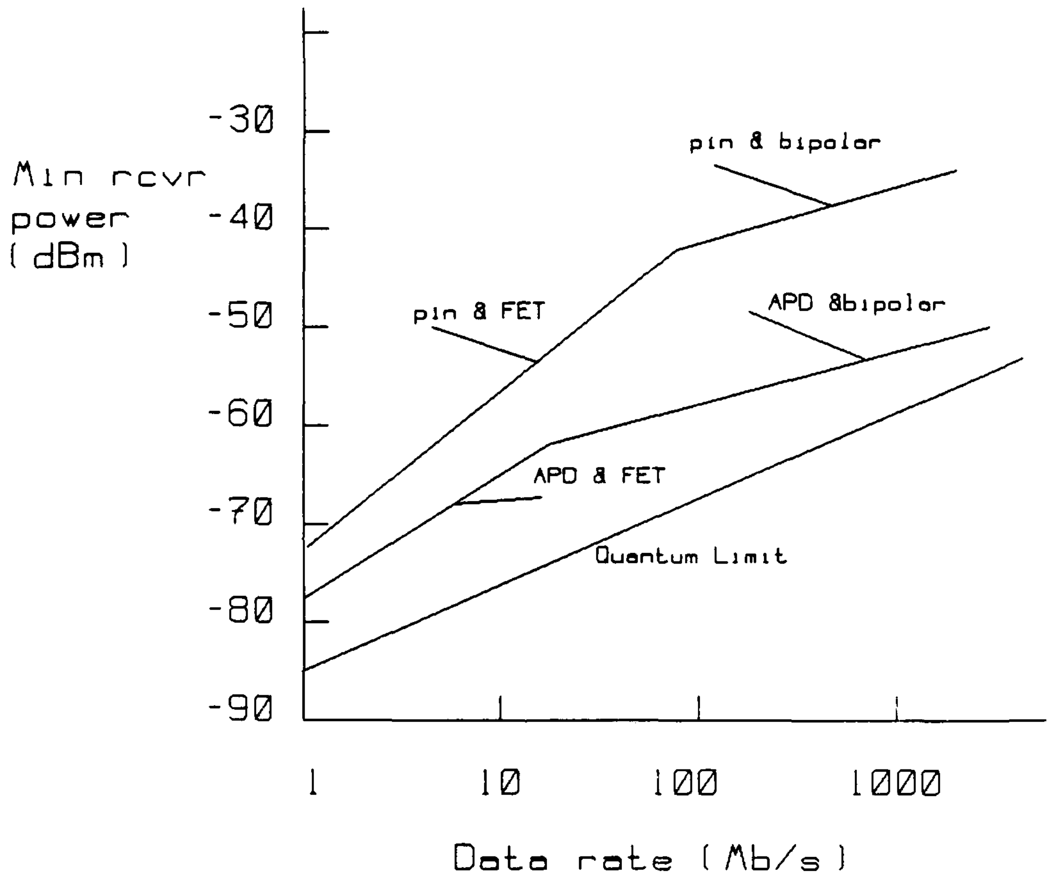

Figure 9. Baud Rate vs Sensitivity
[From Ref. 8]

receivers. While avalanche photodiodes are the most sensitive, they require a 20 to 200 reverse bias voltage. Additional circuitry is required to maintain this reverse bias over temperature variations and to prevent damage. Photodiodes (pin-fets) will provide adequate sensitivity at -32 dBm and overcome the drawbacks of the APD. [Ref. 9: p. 77]

2. Current to Voltage Converter

The low level current produced by the photodiode must be converted to a voltage signal in order to be processed by conventional means. The transimpedance preamplifier design offers an efficient current-to-voltage transformation, wide dynamic optical range, and a linear response which precludes the necessity of an equalization amplifier. The simplest transimpedance design is shown in Figure 10. The output voltage V is given in equation 2.1

$$V = \frac{-R_F I_{diode}}{1 + j2\pi f R_F C / A} \qquad (2.1)$$

where R_F is the feedback resistance, A is the amplifier gain, f is the operating frequency and C is the input capacitance. To maintain linearity over the desired frequency range, the gain (A) must be much greater than $2\pi R_F fC$, this dictates the requirement for high gain-bandwidth product amplifiers. [Ref. 2, pp. 420-424]

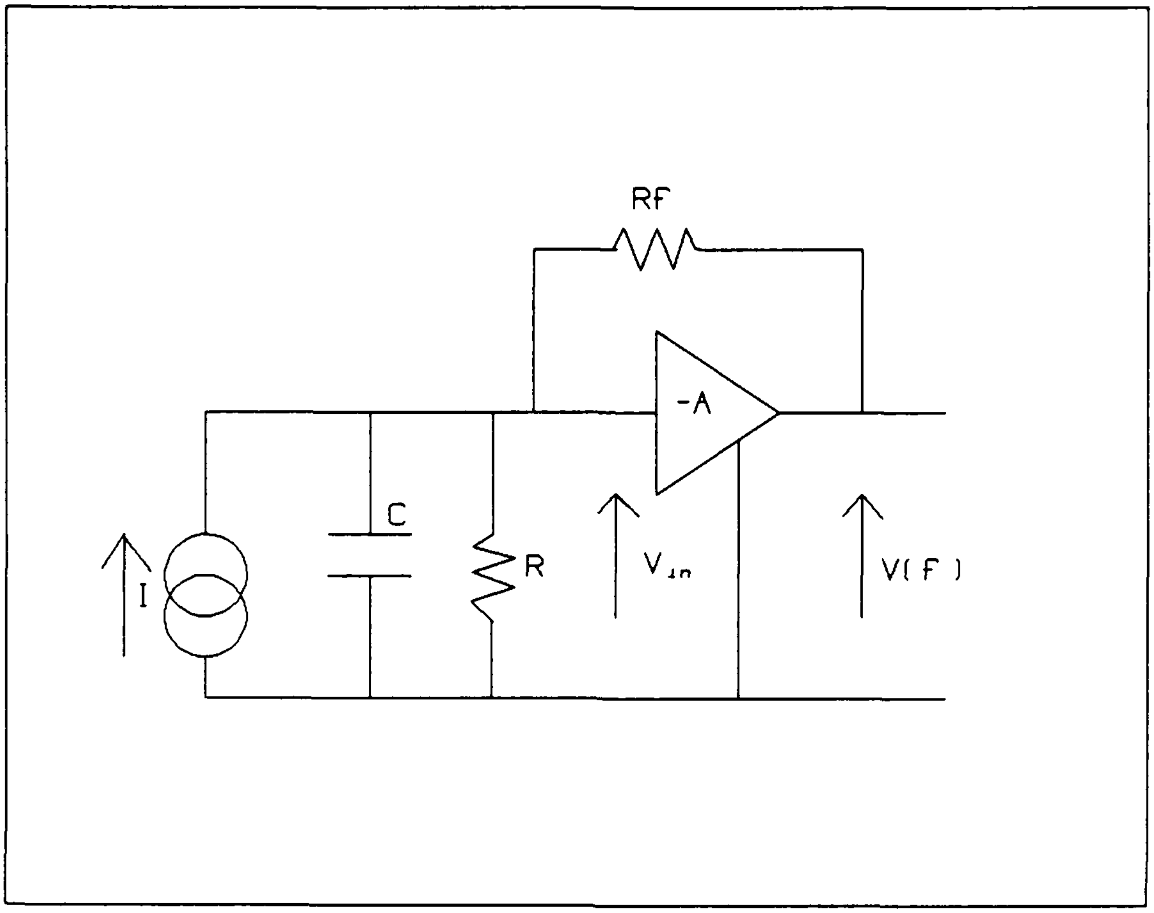

Figure 10. Transimpedance Design

While high speed operational amplifiers are available, protoboard design is severely limited by stray capacitance. Fortunately many detectors are now manufactured incorporating the transimpedance stage into the package. The General Optronic long wavelength (1300 nm) receiver module "GO PIN-FET" is used in the final design. The GO PIN-FET uses an InGaAs tertiary detector which demonstrates an extremely low dark current of less than 10 nA, less than 0.6 pF capacitance and a typical responsivity of 0.65 A/W. The rated sensitivity of this module is shown in Figure 11.

Data Rate [Mbs]	Typ.Power [dBm]
16	-53
34	-50
45	-49
90	-42
140	-40
280	-34

Figure 11. Sensitivity of GO PIN-FET
[From Ref. 10]

A system data rate of 16 Mbs can easily be achieved with -53 dBm of optical power. The unit delivered had a transimpedance of 5200 ohms, a noise voltage of 101 microvolts, and was connected to one meter of 50/120 micron multimode graded index fiber. This multimode fiber eases splicing constraints to the single mode system [Ref. 11: p. 128]. The output of the GO PIN-FET module is determined according to Equation 2.2:

$$V(out) = (P)(R)(T) \tag{2.2}$$

where P is the received optical power, R is the detector responsivity and T is the transimpedance.

3. <u>Linear Amplifier</u>

The GO PIN-FET voltage output can be processed by conventional means. This processing starts with the third element of the basic system, the (ELANTEC 2006) linear amplifier. It must provide sufficient gain to elevate the

integrated detector output above the comparator's threshold. Tests of the prototype receiver show the threshold is 20 mV; therefore, with a received optical power of -29.6 dBm, a third stage gain of 10 is required. The relatively high threshold is a function of the protoboard implementation which contributes to the noise input. This noise can also be significantly increased by high bandwidth amplifiers. As a general rule the amplifier's bandwidth should be limited to a level such that its noise contribution is less than 50% of the integrated detector's noise. The Elantec amplifier has a frequency dependent noise figure of 20 nv/(HZ)$^{\frac{1}{2}}$ below 1 MHz and 3 nV/(HZ)$^{\frac{1}{2}}$ above 1 MHz. It is designed for a gain of 10 with a 50 MHz bandwidth. The noise voltage is 41 microvolts.

4. Coupling and Conditioning

The Elantec amplifier's output is AC coupled to the differential stage. The coupler is formed by a simple RC circuit which maintains a 0.0 volt DC output. This results in the midpoint of the pulse extremes being shifted as the duty-cycle varies, as seen in Figure 12. One output of the

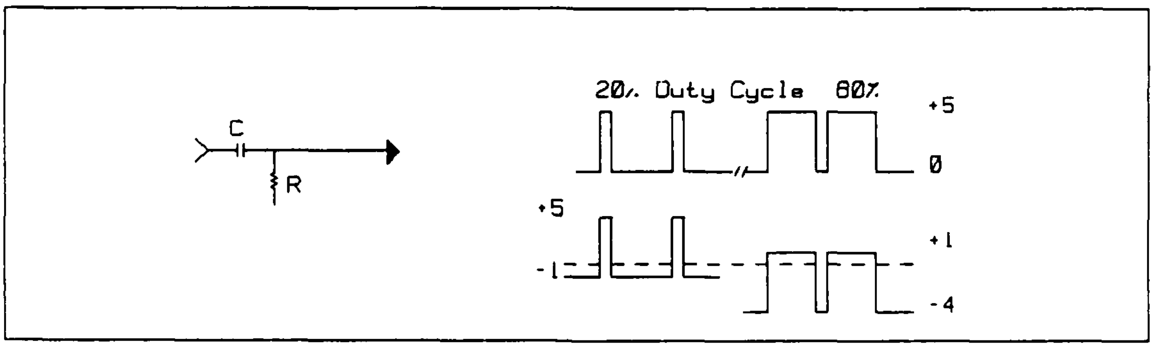

Figure 12. AC Coupler

differential circuit is a scaled replica of a coupled input; the second output is a mirror image of the first, inverted about the 0.0 volt DC axis. The inverted pulse serves as threshold to the comparator, Figure 13. The disadvantage of this circuit, seen in Figure 13, is that, as the duty-cycle changes, the separation between the original and inverted pulse decreases, making the system more susceptible to noise. The bit error rate is therefore a function of the signal-to-noise ratio and the duty-cycle. The signal-to-noise ratio is given in Equation 2.3, where E_{speak} is the maximum voltage of

$$S/N = 20 \log E_{speak}/E_{nrms} \qquad (2.3)$$

the signal pulse and E_{nrms} is the root mean square noise. The probability of bit error, P_e, for a 50% duty-cycle signal is given in Equation 2.4. As the duty-cycle changes, an

$$P_e = 0.5 \operatorname{erfc}(E_{speak}/E_{nrms}) \qquad (2.4)$$

increase of 20 log (0.5/D) in the S/N ratio is required to maintain this bit error rate. Here D is equal to the duty-cycle when the duty-cycle ranges from 0.0 to 0.5, and D is equal to one minus the duty-cycle, when the duty-cycle ranges from 0.5 to 1.0. If the duty-cycle is maintained at 50%, the differential circuit offers the minimum required S/N ratio to achieve a given BER. Other techniques for coupling the signal are compared in Figure 14. The common mode rejection

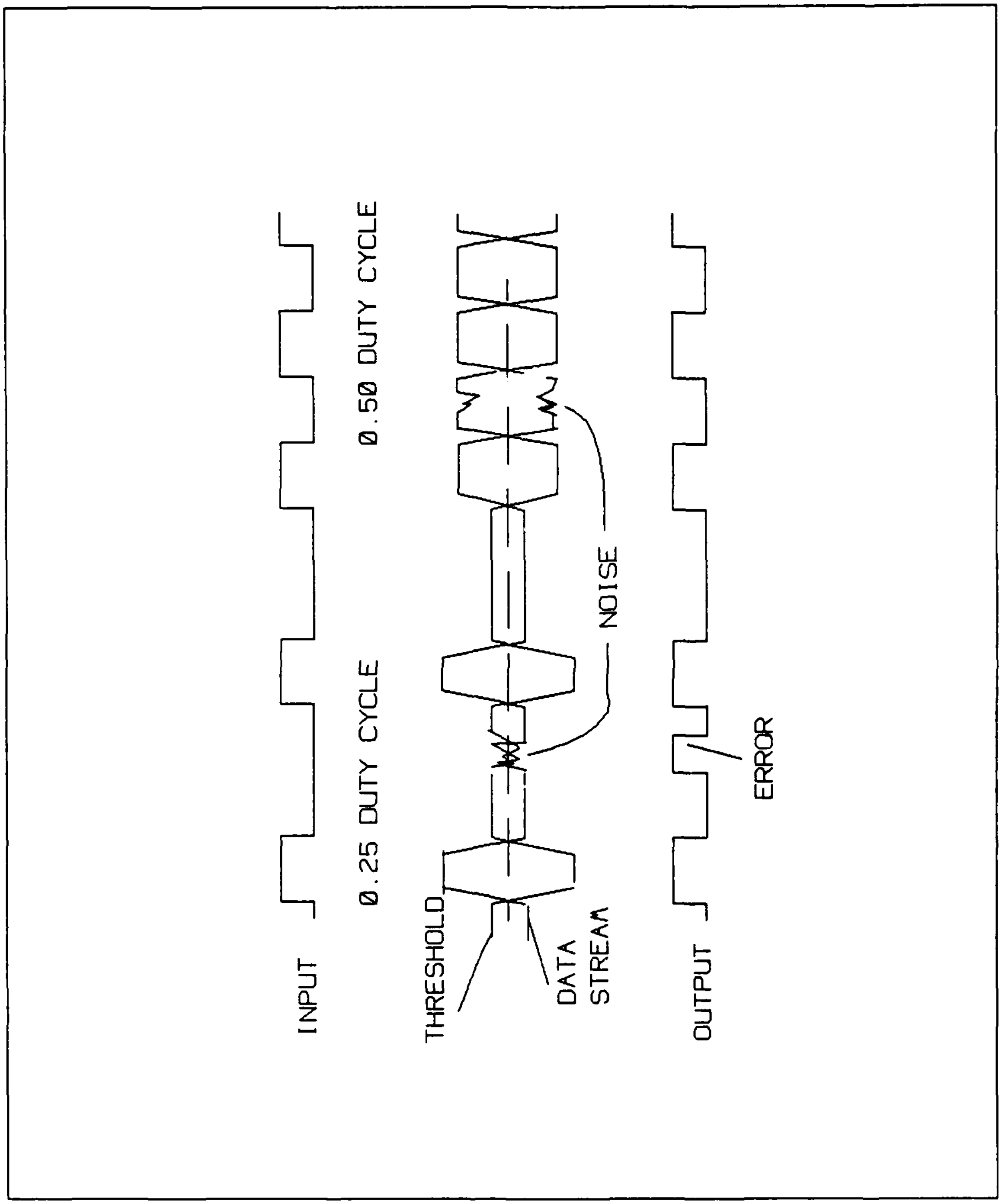

Figure 13. Differential Waveform
[From Ref. 7]

DETECTOR APPROACH	ADVANTAGES	DISADVANTAGES
Single ended AC coupled No Hysteresis	Maximum sensitivity	Requires continuous AC idle-channel-pattern and duty-cycle limits to reject noise as well as a reference voltage that tracks data baseline. No common-mode rejection.
Differential coupled.	No Baseline tracking required, common mode rejection.	Requires continuous AC idle-channel-pattern and duty-cycle limits to reject noise, sacrifice in sensitivity dependent on duty-cycle limits.
Single ended AC coupled with hysteresis.	Doesn't require continuous idle-pattern and duty-cycle limits for noise rejection.	Sacrifices 6 dB in sensitivity. Requires threshold which tracks data stream baseline. No common mode rejection.
Single ended edge type AC coupled with hysteresis.	Doesn't require idle-channel-pattern or duty-cycle limits to reject noise, doesn't require tracking reference voltage.	Sacrifices 8.2 dB in sensitivity. No common mode rejection.
Differential Edge-type AC coupled with hysteresis.	Doesn't require idle-channel-pattern or duty-cycle limits. Doesn't require tracking reference voltage, offers common mode rejection.	Sacrifices 8.2 dB in sensitivity.

Figure 14. Comparison of Coupling Techniques
[From Ref. 3]

and high sensitivity make the ac coupled differential circuit advantageous for low level signals. The differential circuit used (Figure 15) provides a single ended gain of 1.2, a calculated bandwidth of 70 MHz, and a wide dynamic range. The low noise figure of the CA 3127 transistors (typically 2.5 dB) and minimum gain prevent a significant contribution by the differential circuit to the system's noise.

The differential input signal originates from the underwater LM 331 V/F converter. Figures 16 through 18 show the V/F output with a 1.0 V, 5.0 V and 10.0 V DC input, respectively. A one volt DC input produced the 909 Hz pulse train in Figure 16. This signal had a duty-cycle of 0.85. When the input was increased by a factor of 5, the frequency of the output signal (Figure 17) responded linearly increasing to 4.64 KHz, while the duty-cycle decreased to 0.66. With a 10 volt input the V/F output was a 10 KHz pulse train with a 0.25 duty cycle as seen in Figure 18. The effect of this duty-cycle variation on the differential output is shown in Figures 19 through 21. The outputs of the differential circuit with the 909 Hz, 0.85 duty-cycle input is shown in Figure 19. The original pulse train has been shifted downward maintaining a 0.0 V DC level; the image of this pulse train serves as the comparator threshold. The smallest separation between the signal and the threshold is 0.051 V, providing a noise tolerance of 0.025 V. Figure 20 shows the outputs of the differential circuit with the 4.64 KHz, 0.66

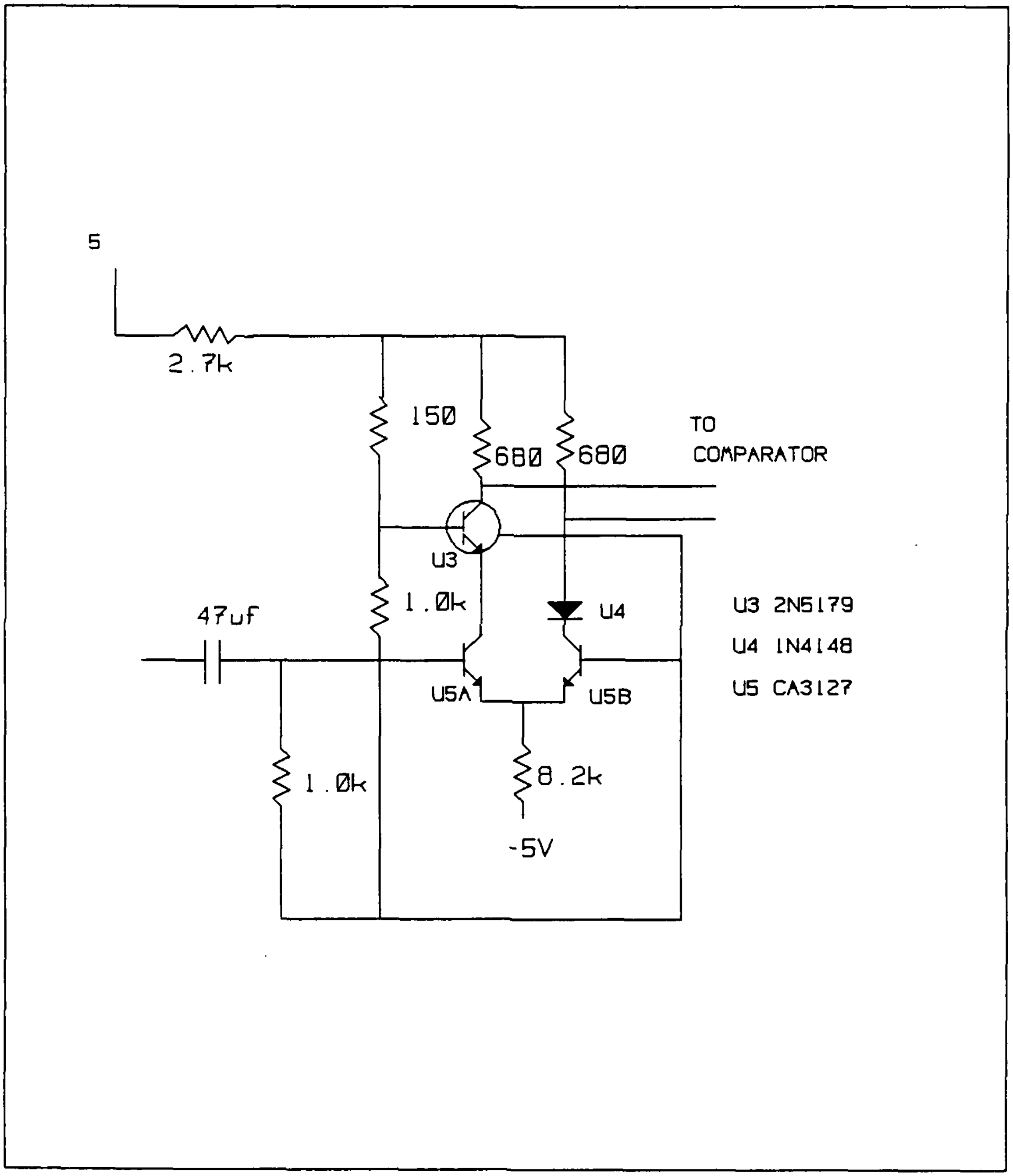

Figure 15. Differential Amplifier
[From Ref. 12]

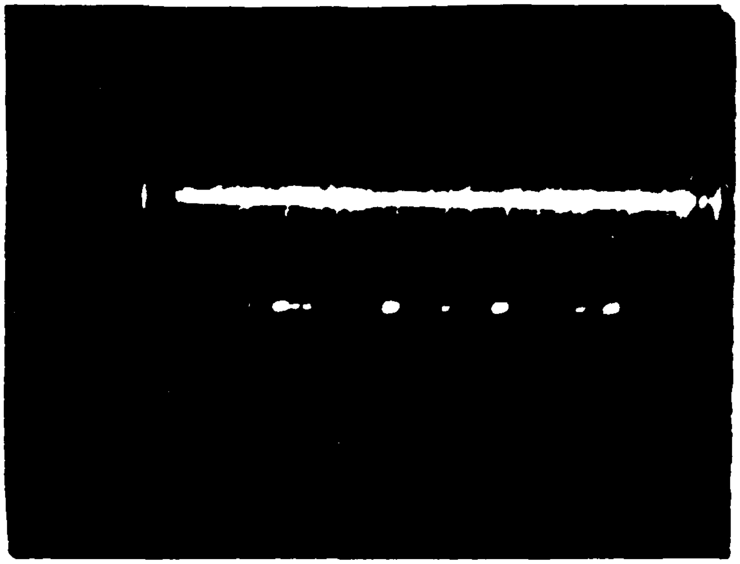

Figure 16. Input 1 V Frequency 909 Hz Duty-cycle 0.85
1 V/Div 0.5 ms/Div

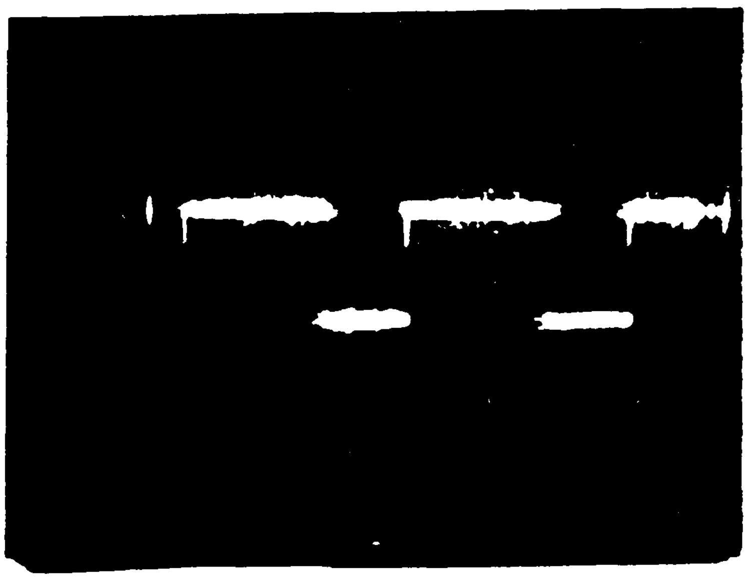

Figure 17. Input 5 Volts Frequency 4.64 KHz Duty-cycle 0.66
1 V/Div 0.050 ms/Div

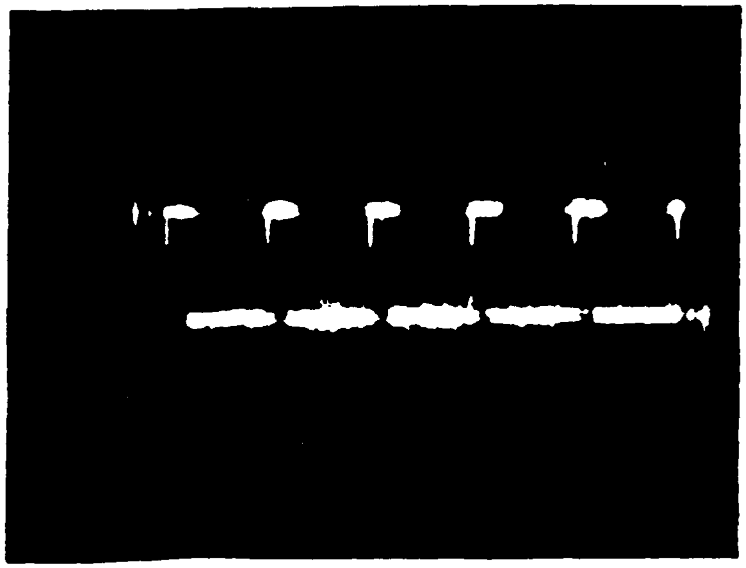

Figure 18. Input 10 V   Frequency 10 KHz   Duty-Cycle 0.20
1 V/ Div   0.05 ms/Div

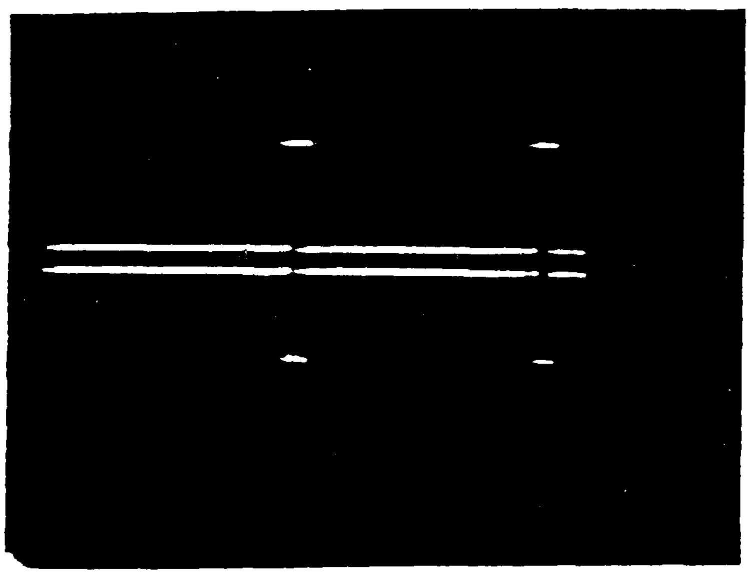

Figure 19. Differential Output Duty-Cycle 0.85
0.1 V/Div   0.2 ms/Div

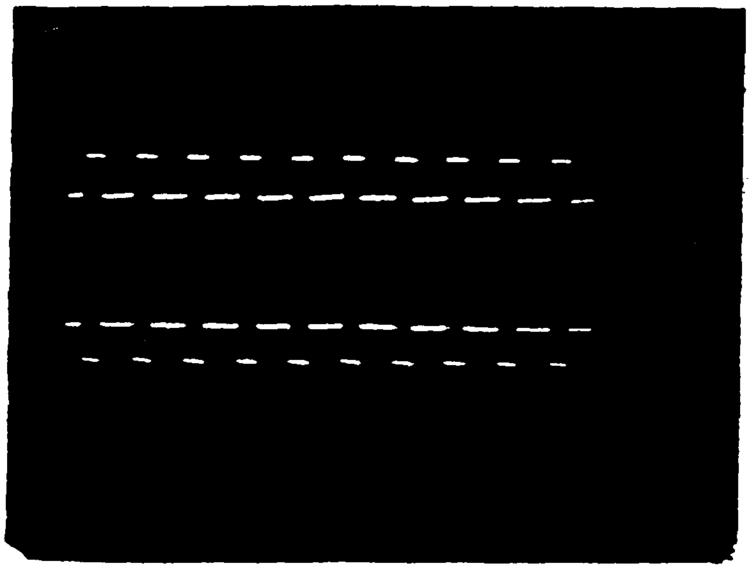

Figure 20. Differential Output Duty-Cycle 0.66
0.1 V/ Div 0.2 ms/Div

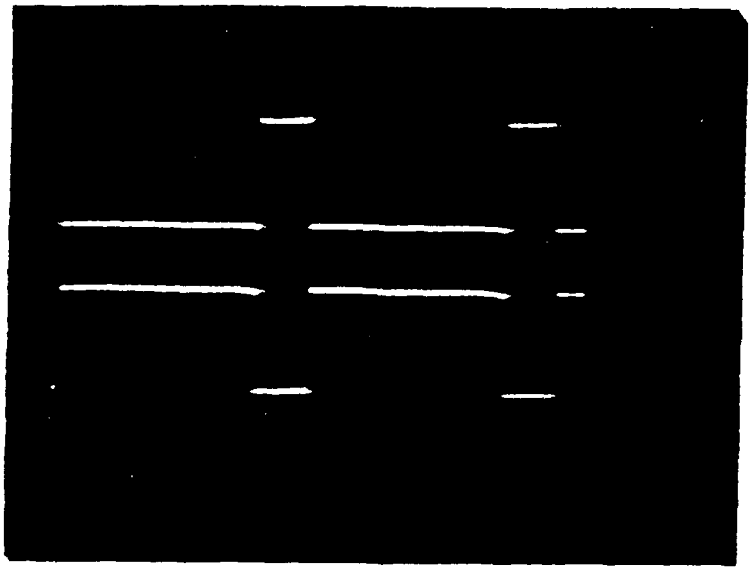

Figure 21 Differential Output Duty-Cycle 0.20
0.1 V/ Div 0.2 ms/ Div

duty-cycle signal. The minimum separation of these outputs is 0.225 V, providing a noise tolerance of 0.11 V. The maximum noise immunity is obtained with a 0.50 duty-cycle signal which provides a noise tolerance of 0.16 V. Figure 21 shows the differential outputs for the 0.20 duty-cycle signal The noise immunity has been decreased to 0.06 V. The duty-cycle variation from 0.2 to 0.85 requires a S/N ratio increase of 10.45 dB. A second stage voltage of 2.13 mV and noise of 0.15 mV yields an adjusted S/N ratio of 23.0 dB which supports a BER of 10^{-6}.

5. Comparator

The Linear Technology (LT 1016) comparator offers several advantages in fiber optic system applications. Its 10 ns rise time supports high data rate operations. This rise time is achieved by a unique output stage that provides active drive in both directions but avoids large current spikes normally found in "totem pole stages". An important feature is the low quiescent negative power supply (3 mA), which increases the system lifetime [Ref. 13]. The LT 1016 is extremely susceptible to oscillations caused by improperly bypassed power supplies. An inch of wire between the bypass capacitor and the LT 1016 may cause oscillations, and capacitors with good high frequency characteristics must be used. [Ref. 13] The receiver design was tested on a protoboard which contributes to the difficulty in preventing

oscillations of the LT 1016. Printed circuit board implementation should incorporate a grounding plane to minimize stray capacitance and inductance. The complete receiver model schematic is shown in Figure 22.

6. Logic Interface

The logic interface is an LM 331 configured as a frequency-to-voltage converter, as shown in Figure 23. The output voltage is calculated from Equation 2.5

$$V_{out} = f_{in}\ (2.09\ V_S)\ (R_L/R_S)\ R_t\ C_t, \qquad (2.5)$$

and can be calibrated with the 5000 ohm potentiometer to respond with the same linearity as the modulating V/F converter, thereby offering an accurate reproduction of the modulating voltage. The DC output is read with a Fluke programmable multimeter that is triggered by the shore controller.

7. System Risetime

A NRZ signal requires the system risetime be less than 0.7 times the pulse width. The risetime is given in Equation 2.6:

$$t_{sys} = (t_s^2 + t_{mat}^2 + t_{det}^2 + t_{amp}^2 + t_{comp}^2 + t_{modal}^2)^{1/2} \qquad (2.6)$$

where t_s is the source risetime, t_{mat} is the material dispersion, t_{wg} is the wave guide dispersion, t_{det} is the detector module risetime, t_{amp} is the linear amplifier risetime, t_{comp} is the comparator risetime and t_{modal} is the

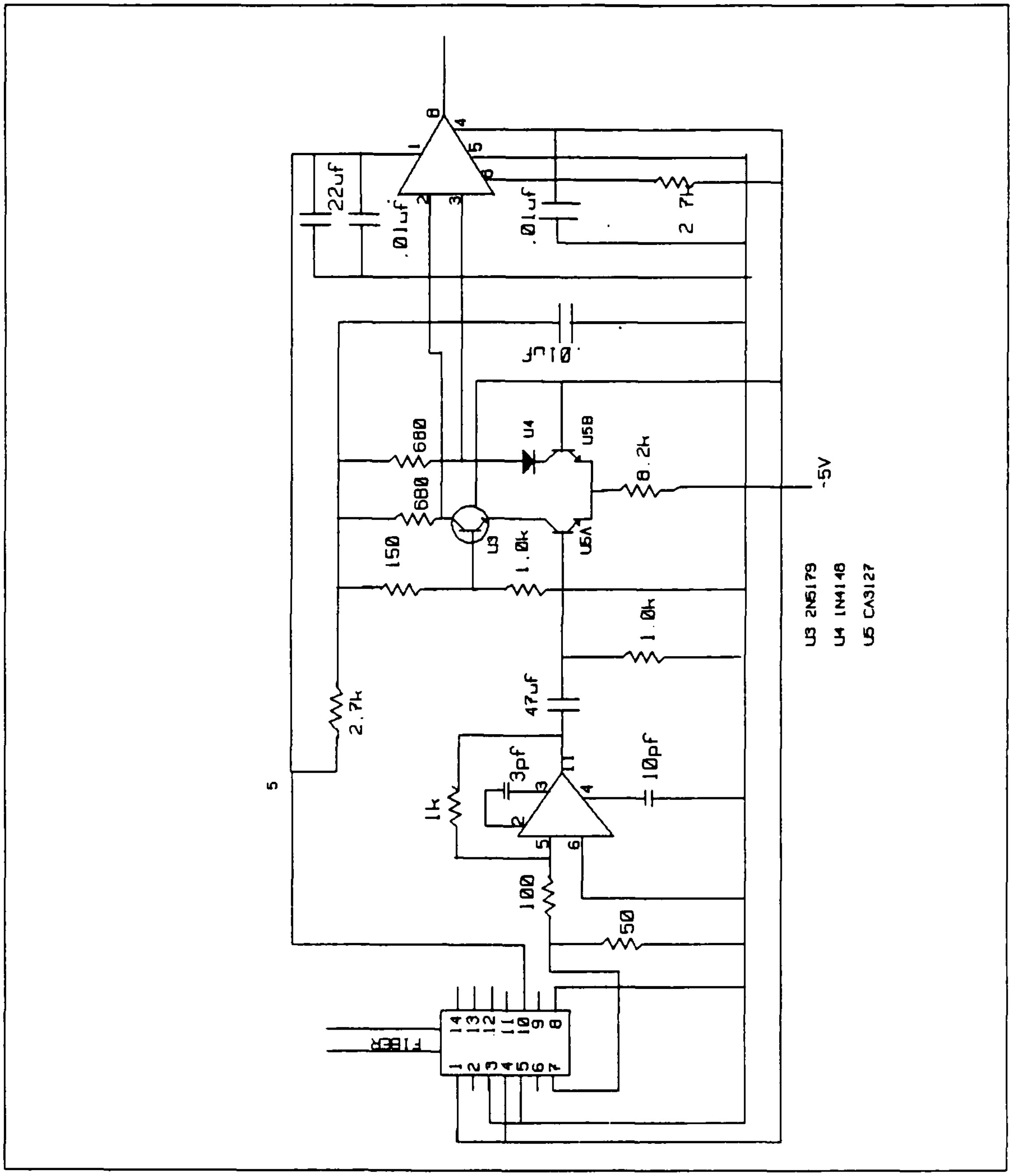

Figure 22. Receiver Module

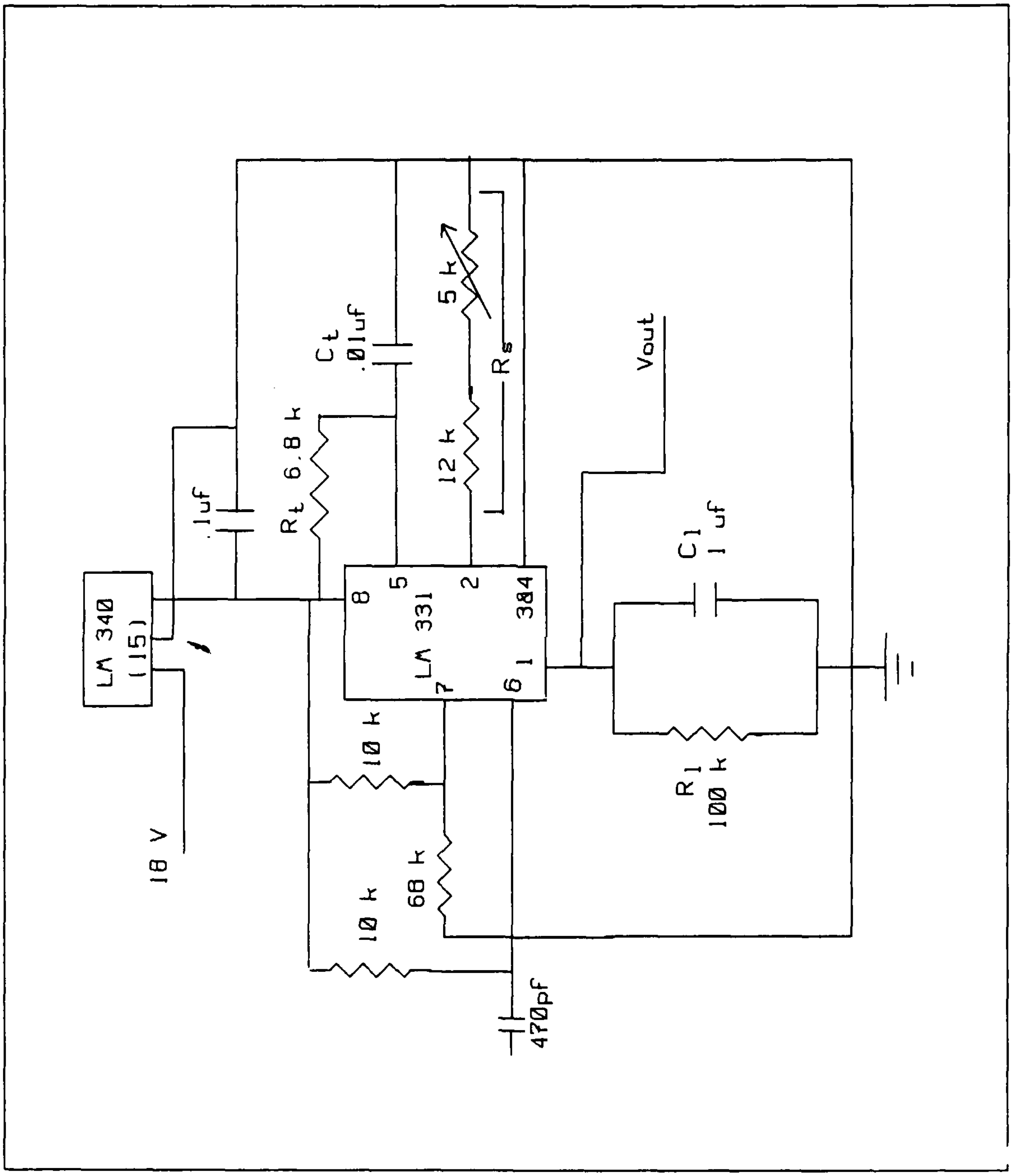

Figure 23. Logic Interface
[From Ref. 2]

modal dispersion [Ref. 10: pp 7-19]. Modal dispersion is not present in single mode fiber and at an operating wavelength of 1300 nm, material and waveguide dispersion offset each other [Ref. 10: pp 2-28]. The principal dispersive elements are the Lasertron source (0.5 ns), the GO PIN-FET receiver (2.5 ns), the EL 2006 amplifier (12 ns) and the LT 1016 comparator (10 ns). With these elements the system risetime is 15.8 ns, which supports an upper data rate of 44 Mbs.

C. SHORE CONTROLLER

The entire system is controlled by an IBM compatible computer through a GPIB bus interface. The controlling program (Appendix A) is written in BASIC, and interleaved with the GPIB subprograms provided with the National Instruments GPIB control card [Ref. 14]. Upon execution the user is requested to enter the sampling interval (1 to 59 minutes). At each sample interval the program performs the following sequence:

1) commands the Wavetek function generator, which modulates the laser to output a DC signal,

2) triggers the Fluke multimeter,

3) records the multimeter response and date/time on drive A: in file BATDAT.DAT,

4) directs the function generator to output a 5 MHz TTL signal,

5) triggers the Fluke multimeter,

6) records the multimeter response and date/time on drive

A: in file CONVERT.DAT, and

7) waits for next interval.

Each multimeter response and date/time entry requires approximately 45 bytes, so that if data is taken at 1 minute intervals, a double sided double density disk can hold 2.7 days of information. To avoid unintentional activation of the U/W control system, the controlling program should be interrupted only during a wait period. At that time, the data disk can be replaced and the program restarted.

An alternate control program, Appendix B, was written to support a parallel development of a simplex system. In this design the underwater system remains dormant until activated by a microprocessor. At that time a reference signal, indicating which of two sampled voltages will modulate the V/F Converter, is transmitted [Ref. 15]. The shore system continuously monitors the link, determines which reference was transmitted, and records the data in the appropriate file. The modulating technique, receiver design, and GPIB multimeter interface are identical with the bidirectional design. The simplex approach offers simpler link design at the expense of control, and demonstrates the adaptability of using the GPIB as a controller.

1. GPIB

The National Instruments GPIB-PC2 control board serves as the switching center for communications between the computer, multimeter and function generator. The control

board can handle up to 16 devices that receive instructions through the BASIC language interface programs. The most commonly needed I/O functions of the BASIC language interface are IBWRT and IBRD; they are used to write instructions and read data from attached equipment. An example of a call to IBWRT is:

```
WRT$ = "foc2i" call IBWRT (BRD2%, WRT$)
```

where BRD2% has been defined previously as the Wavetech generator. The bit string contained in WRT$ directs the generator to shift to a zero hertz signal. In response to this call the device status and error number are updated and returned in IBSTA% and IBERR% respectively. The 16 bit "status word" IBSTA% format is shown in Figure 24. This format is also used by the command:

```
MASK%=H4800. Call IBWAIT (BRD1%,MASK%).
```

This instruction delays program execution until either a previously designated time has elapsed, or a service request is received.

An example of a call to IBRD is:

```
RD$=SPACE$(14) CALL IBRD(BRD%,RD$).
```

RD$ contains the number of bytes in the character string to be received and the actual character string upon return. The BASIC command "NUM" is then used to convert the string value to its numerical equivalent. IBRD also updates IBSTA% and IBERR%. [Ref. 14: pp 4A1-4A99]

DESCRIPTION	MNEMONIC	BIT.POS.	HEX. VALUE
GPIB error	ERR	15	8000
Time limit exceeded	TIMO	14	4000
GPIB-PC detect END or EOS	END	13	2000
SRQ on	SRQI	12	1000
Device requesting service	RQS	11	800
I/O completed	CMPL	8	100
GPIB-PC in Lockout State	LOK	7	80
GPIB-PC in Remote State	REM	6	40
GPIB-PC Controller in charge	CIC	5	20
Attention is asserted	ATN	4	10
GPIB-PC is Talker	TACS	3	8
GPIB-PC is Listener	LACS	2	4
GPIB-PC in Device Trigger	DTAS	1	2
GPIB-PC in Device Clear	DCAS	0	1

Figure 24. GPIB Status Word
[From Ref. 14]

2. GPIB-410

The bus activity was monitored with an IBM personal computer through a GPIB-410 interface board. This interface not only allows continuous monitoring but also direct manipulation of the bus using sixteen simulated switches. The status, and simulated switches are displayed in the monitor window. Below the monitor window the "analyzer window" is displayed. In this window four screens which interface with the bus may be called:

1) Capture Settings Screen; used to specify the quantity and methodology of recording data.

2) Trigger Setting Screen; used to enter action to be taken when a specified pattern is required.

3) Capture Display Screen; used to display the captured data for analysis

4) Pattern Generator Screen; used for high speed transmission of data from the GPIB-410 to the bus.

In early development the Capture screen was most useful in isolating program errors. For example the following command was sent to the multimeter:

```
WRT$="NO17E+2PIFIRST3?":CALL IBWRT(BRD%,WRT$)
```

This command, among other things, instructs the multimeter to set the request service bit (SRQ) when the data is stable. The GPIB-410 was directed to capture data when the SRQ bit was set or Data transfer occurred. This proved an easy method to trace the sequence of events, determine data validity, and monitor the control program. Rapid identification of bus and program errors were made possible with this interface and monitoring of IBSTA%. [Ref. 16]

3. Fluke 8840A Digital Multimeter

The Fluke 8840A multimeter is a fully programable true RMS meter capable of DC resolution from 1 microvolt to 1000 volts. The programmable command set duplicates front panel buttons and allows easy construction of command strings. The multimeter was set in a talk/listen mode and externally triggered by the control program. The data was read by the control program and stored on disk.

4. Wavetek Model 270 Function Generator

The model 270 Wavetech is a fully programmable 0.01 Hz to 12 MHz multifunction generator. Each function, frequency and operating characteristic can be accessed through the GPIB bus. The generator was directed to shift between a 5 MHz and 0 Hz output. This signal was used to modulate a Photodyne 1300 nm LED optical signal generator during system test.

5. Photodyne Model 7750XR Optical Signal Generator

The Photodyne LED optical generator was used during controller and receiver evaluation. Its optical output is peaked at 1300 nm and launches approximately 50 microwatts into 50/125 micron fiber. The front panel allows external TTL frequency control as high as 20 Mbs.

D. UNDERWATER CONTROLLER

The underwater circuitry, Figure 25, monitors and implements instruction from the shore-based controller. The receiver module is a replica of Figure 22. The receiver output is fed through a high pass filter allowing only the 5 Mbs control signal to pass. A momentary drop of this control signal activates the switch, V/F converter and laser module. The length of active period is determined by LM 555 timers, during this period the control signal is used to select the desired voltage. The voltage is prescaled and serves as the input to LM 331 V/F converter which modulates the laser.

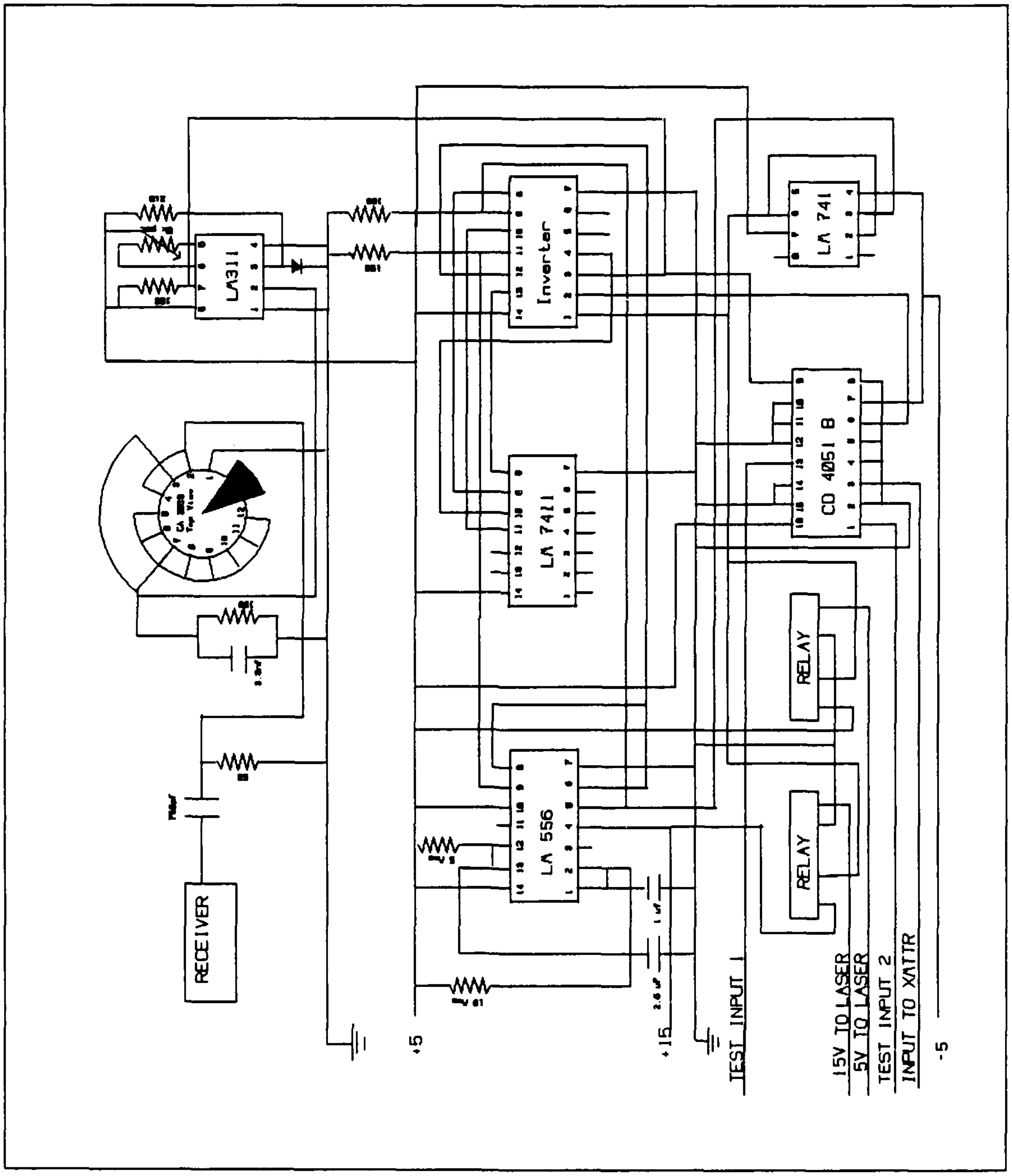

Figure 25. Underwater Circuitry

1. Timing Circuits

How long power is made available to the laser source is determined by a LM 555 timer which is triggered from the shore controller. The controlling signal is a 5 Mbs, 50% duty cycle pulse train transmitted continuously by the shore station. The output of the underwater receiver is fed through a high pass filter, rectified and compared to a 0.7 V threshold. The rectified 5 Mbs control signal will have sufficient amplitude to cross the threshold and activate the comparator. The comparator and timer outputs are combined by an "OR" function. The output of the constructed OR gate serves as the trigger for the LM 555. Feeding back the timers' output in essence disconnects the control signal from the trigger mechanisms when the timers are on. If both timers are off, the drop in the 5 Mbs control signal will force the OR gate output low, and trigger the timers. Two timers, both triggered simultaneously, are used. The first timer, set for 5 seconds output, is buffered and switches the Claire relays open providing 5 and 15 volt sources to the transmitting circuitry. In addition the buffered output is inverted and connected to the inhibit pin of the CD 4051 multiplexer. When the first timer is off, the buffered output inhibits all input channels and maintains the multiplexer at its lowest current drive (5 microamps maximum).

The second timer (set for 7 seconds) provides a margin of safety for the control signal to be reestablished to prevent system oscillation.

2. Switching

During the first timer's ON period, the control signal is used to select the desired voltage. The switching mechanism is a CD 4051 multiplexer activated by the LM 555 timer; the control signal is connected to the select pin via the threshold comparator. This allows direct control of the CD 4051 output by the shore station.

3. Modulating Circuitry

The modulating circuitry in Figure 26 includes the prescaling input amplifier (LM 123J) which is required to elevate the 0.1 to 1 volt sampled voltage to a 1 to 10 volts. The TTL output frequency of the LM 331 is varied linearly from 1 KHz to 10 KHz and is given by Equation 2.7:

$$f_{out} = \frac{10\ V_{in} R_s}{2.09\ V_{cc} R_1 R_t C_t} \qquad (2.7)$$

where R_s, R_l and R_t are the source, load and timing resistances [Ref. 2: pp 11-14]. The LM 331 frequency output has a $\pm$ 3 percent linearity with the voltage input, but suffers the frequency to duty-cycle limitations previously discussed.

4. Power Consumption

In the quiescent state the underwater system requires 56 mA of current from the 5 volt source. Once deployed, the bidirectional system lifetime is dependent upon

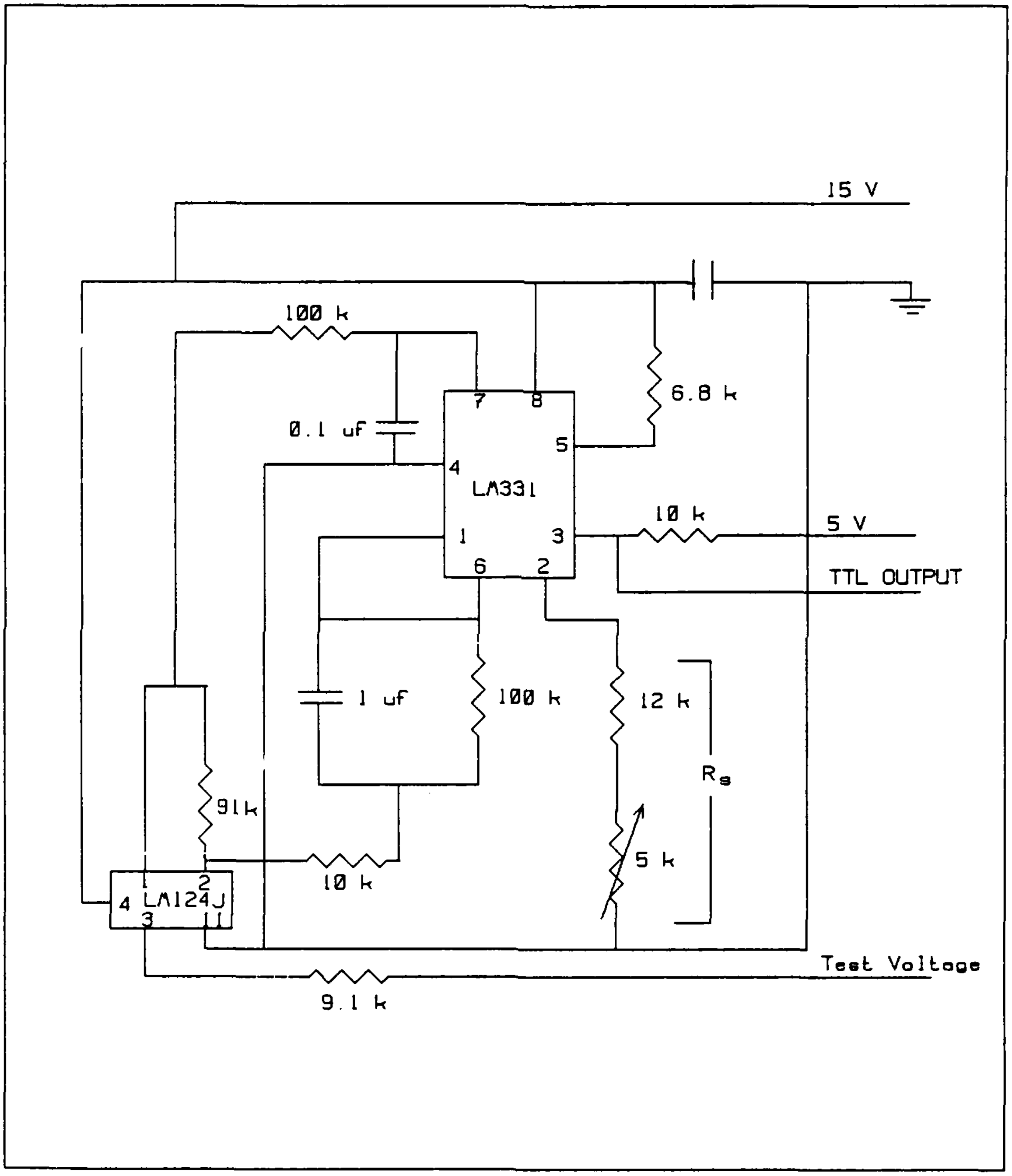

Figure 26. Modulating Circuitry

this quiescent current. For continuous operation the LED or laser drive current becomes the limiting factor. A comparison of the two approaches is show in Figure 27. The power savings of the proposed system offers a 92% reduction of the 12 volt battery requirements. While this is a significant improvement, 62 six volt batteries would still be needed for a single year's operation.

	CONTINUOUS		SHORE ACTIVATED	
SOURCE	6 volt	12 volt	6 volt	12 volt
AMP HR RATE	8	6.5	86.5	
CURRENT REQ.	66 mA	14 mA	56 mA	14 mA
LIFE EXPECTED	120 hr	464 hr	140 hr	5568 hr

Figure 27. Power Consumption

III. TEST AND EVALUATION

Laboratory tests were designed to evaluate the receiver and data recording system. LED sources were employed as laser drive circuits were under parallel development.

The input pins (1 and 13) of the multiplexer, Figure 25, were connected to two variable power supplies, simulating test data. Pin 13 was varied from 0.5 V to 0.1 V; pin 1 was varied from 1 V to 0.5 V, thereby testing the battery range. The system was deactivated while test voltage adjustments were made; this allowed the Fluke multimeter to be used to measure the input data and avoid calibration errors.

The extreme sampling intervals of the recording system, 1 and 59 minute sampling intervals, were conducted. The results are in Appendix C, and summarized in Figure 28.

INPUT (VOLTS)	AVERAGE OUTPUT (VOLTS)	AVERAGE ERROR
1.000	1.050	+5.0%
0.908	0.945	+4.0%
0.788	0.817	+3.6%
0.694	0.715	+3.0%
0.587	0.611	+4.0%
0.510	0.521	+2.1%
0.396	0.394	-0.5%
0.301	0.294	-2.3%
0.206	0.190	-7.7%
0.145	0.129	-11.0%

Figure 28. Test Results

The system demonstrated an overall accuracy of 4.7% with decreased accuracy on low end data, a 0.1V input could not be

recorded and a 0.14 V input resulted in a 11% error. Performance degradation was attributed first to the 80 ohm input resistance of the multiplexer which resulted in a slight voltage drop, second, to nonlinearity of the LM 331 and third, to improper adjustment of the prescaling amplifier. Measurement at the multiplexer input and output showed a minimal voltage drop across the internal 80 ohm resistor. The poor performance at the low end was mainly attributed to an improperly adjusted prescaler. The LM 331 requires an input voltage of at least one volt for proper operation, with a 0.1 volt input the prescaling amplifier only provided a 0.91 V output. This effect combined with the V/F converter calibrated at the high end, resulted in larger data errors for low voltage inputs.

IV. CONCLUSION AND RECOMMENDATIONS

The original 2.8 km system range limitation was overcome by using longwave length laser sources and single mode fiber. This provided minimum fiber losses, but attention to splice, coupling and connector preparations become vital with single mode fiber to minimize installation losses. The data format itself raised the required signal to noise ratio due to the LM 331 frequency to duty-cycle dependence. An alternate V/F converter which maintains a 50% duty-cycle should be substituted.

The designed system takes advantage of the frequency bandwidth of fiber optics by using a method of frequency separation to transmit the activating switching signals. The simple design allowed the selection between only two voltages; this should be expanded for growth as new data requirements are presented.

The data collection system, based on the GPIB bus interface, proved to be an efficient and versatile system. The ease of programming and high speed interface with up to 15 devices extends system capability beyond simple microprocessor controllers. The controlling program, written in BASIC was easily modified, however, a compiled language may be required when higher recording rates are desired.

Routing these files to floppy disks increased the transportability of data, high density or hard disk drives should be used for extended unattended operation.

The design does fall short of extending the system lifetime. The 56 mA of drive current for the receive module would still require 62 six volt storage cells. A simplex system, with the underwater component controlled by a low power microprocessor and clock, would sufficiently extend the lifetime, but sacrifice controllability. The next development should combine these two techniques, the underwater components incorporating the receive circuitry, the low power clock activating a receive window, and instructions passed to the microprocessor during this interval.

APPENDIX A

This appendix contains the source listing of the program named GPRM3. This interactive program is written in BASIC and is used in conjunction with a GPIB interface card to control the operation of a Fluke programmable multimeter and a Wavetek function generator. The multimeter, function generator, and control program form the nucleus of a bidirectional control system.

```
1        CLEAR   ,59300!          ' BASIC Declarations
6        IBINIT1 = 59300!
11       IBINIT2 = IBINIT1 + 3    ' Lines 1 through 6 MUST be
         include in your program.
16       BLOAD "bib.m",IBINIT1
21       CALL IBINIT1(IBFIND,IBTRG,IBCLR,IBPCT,IBSIC,IBLOC,
         IBPPC,IBBNA,IBON ,IBRSC,IBSRE,IBRSV,IBPAD,IBSAD,
         IBIST,IBDMA,IBEOS, IBTMO,IBEOT,IBRDF ,IBWRTF)
26       CALL IBINIT2(IBGTS,IBCAC,IBWAIT,IBPOKE,IBWRT,IBWRTA,
         IBCMD,IBCMDA,IBR,IBRDA,IBSTOP,IBRPP,
         IBRSP,IBDIAG,IBXTRC,IBRDI,IBWRTI,IBRDIA,IBWRTI,
         IBSTA%,IBERR%,IBCNT%)
31       REM Optionally include the following declarations in
         your program.
36       REM They provide appropriate mnemonics by which
41       REM to reference commonly used values.
         Some mnemonics (GET%, ERR%,
46       REM END%, ATN%) are preceded by "B" in order to
         distinguish them from
51       REM BASIC keywords.
56       REM
61       REM GPIB Commands
66       UNL% = &H3F      ' GPIB unlisten command
71       UNT% = &H5F      ' GPIB untalk command
76       GTL% = &H1       ' GPIB go to local
81       SDC% = &H4       ' GPIB selected device clear
86       BGET% = &H8      ' GPIB group execute trigger
91       TCT% = &H9       ' GPIB take control
96       LLO% = &H11      ' GPIB local lock out
101      DCL% = &H14      ' GPIB device clear
106      PPU% = &H15      ' GPIB ppoll unconfigure
111      SPE% = &H18      ' GPIB serial poll enable
116      SPD% = &H19      ' GPIB serial poll disable
121      PPE% = &H60      ' GPIB parallel poll enable
126      PPD% = &H70      ' GPIB parallel poll disable
131      REM
136      REM GPIB status bit vector
141      REM global variable IBSTA% and wait mask
146      BERR% = &H8000   ' Error detected
151      TIMO% = &H4000   ' Timeout
156      BEND% = &H2000   ' EOI or EOS detected
```

```
161      SRQI% = &H1000   ' SRQ detected by CIC
166      RQS% = &H800     ' Device needs service
171      CMPL% = &H100    ' I/O completed
176      LOK% = &H80      ' Local lockout state
181      REM% = &H40      ' Remote state
186      CIC% = &H20      ' Controller-In-Charge
191      BATN% = &H10     ' Attention asserted
196      TACS% = &H8      ' Talker active
201      LACS% = &H4      ' Listener active
206      DTAS% = &H2      ' Device trigger state
211      DCAS% = &H1      ' Device clear state
216      REM
221      REM Error messages returned in global
         variable IBERR%
226      EDVR% =  0       ' DOS error
231      ECIC% =  1       ' Function requires board to be CIC
236      ENOL% =  2       ' Write function detected
         no Listeners
241      EADR% =  3       ' Interface board not addressed
                            correctly
246      EARG% =  4       ' Invalid argument to function call
251      ESAC% =  5       ' Function requires board to be SAC
256      EABO% =  6       ' I/O operation aborted
261      ENEB% =  7       ' Non-existent interface board
266      EOIP% = 10       ' I/O operation started before
                            previous operation completed
271      ECAP% = 11       ' No capability for operation
276      EFSO% = 12       ' File system operation error
281      EBUS% = 14       ' Command error during device call
286      ESTB% = 15       ' Serial poll status byte lost
291      ESRQ% = 16       ' SRQ remains asserted
296      REM
301      REM EOS mode bits
306      BIN% = &H1000    ' Eight bit compare
311      XEOS% = &H800    ' Send EOI with EOS byte
316      REOS% = &H400    ' Terminate read on EOS
321      REM
326      REM Timeout values and meanings
331      TNONE% =   0     ' Infinite timeout (disabled)
336      T10US% =   1     ' Timeout of 10 us (ideal)
341      T30US% =   2     ' Timeout of 30 us (ideal)
346      T100US% =  3     ' Timeout of 100 us (ideal)
351      T300US% =  4     ' Timeout of 300 us (ideal)
356      T1MS% =    5     ' Timeout of 1 ms (ideal)
361      T3MS% =    6     ' Timeout of 3 ms (ideal)
366      T10MS% =   7     ' Timeout of 10 ms (ideal)
371      T30MS% =   8     ' Timeout of 30 ms (ideal)
376      T100MS% =  9     ' Timeout of 100 ms (ideal)
381      T300MS% = 10     ' Timeout of 300 ms (ideal)
386      T1S% =    11     ' Timeout of 1 s (ideal)
391      T3S% =    12     ' Timeout of 3 s (ideal)
396      T10S% =   13     ' Timeout of 10 s (ideal)
```

```
401      T30S% =   14     ' Timeout of 30 s (ideal)
406      T100S% =  15     ' Timeout of 100 s (ideal)
411      T300S% =  16     ' Timeout of 300 s (ideal)
416      T1000S% = 17     ' Timeout of 1000 s (maximum)
421      REM
426      REM Miscellaneous
431      S% = &H8         ' Parallel Poll sense bit
436      LF% = &HA        ' Line feed character
441      REM
446      REM Application program variables passed to
451      REM GPIB functions
456      REM
461      CMD$ = SPACE$(10)        ' command buffer
466      RD$ = SPACE$(255)        ' read data buffer
471      WRT$ = SPACE$(255)       ' write data buffer
476      BNAME$ = SPACE$(7)       ' board name buffer
481      BDNAME$ = SPACE$(7)      ' board or device name buffer
486      FLNAME$ = SPACE$(50)     ' file name buffer
488      INPUT "Enter sample period in minutes, 59 min. max.
         " ,PERIOD
491      BDNAME$ = "gpib0"
496      CALL IBFIND (BDNAME$,BRD0%)
501      BDNAME$ = "flukemm"
506      CALL IBFIND (BDNAME$,BRD1%)
507      BDNAME$ = "funcgen"
508      CALL IBFIND (BDNAME$,BRD2%)
516      V% = 13
521      CALL IBTMO (BRD1%,V%)
522      CALL IBTMO (BRD2%,V%)
536      MEAS = 1
545      FILE$ = "a:batdat.dat"
550      OPEN FILE$ FOR APPEND AS 3
555      FLE$ = "a:convert.dat"
560      OPEN FLE$ FOR APPEND AS 1
570      WHILE MEAS
585      WRT$ = "f5c2i"  :  CALL IBWRT (BRD2%,WRT$)
586      SEC= VAL (MID$(TIME$,7,2))
587      MIN = VAL (MID$(TIME$,4,2))
606      WRT$ = "f5000000c2i" : CALL  IBWRT (BRD2%,WRT$)
610      GOSUB 670
615  WEND
670      J = 0
675      RECORD = 1
680  WHILE RECORD
685      CALL IBCLR (BRD1%)
690    WRT$ = "*N0.17E+2 P1F1R3T3?" : CALL IBWRT (BRD1%,WRT$)
695      MASK%= &H4800 : CALL IBWAIT (BRD1%,MASK%)
700      PRINT IBSTA%
705      RD$ = SPACE$(14) : CALL IBRD (BRD1%,RD$)
710      NUM = VAL(RD$)
715      PRINT NUM
725      TIM$ = TIME$
```

```
730       DAT$ = DATE$
740       IF (IND=1) THEN PRINT #1,NUM;" volts ";"  ";DAT$;"
          ";TIM$
745       J = J+1
750       IF J = 3  THEN  RECORD =0
755   WEND
756       NUM = NUM/10
758       PRINT #1,NUM;" volts ";"  ";DAT$;"   ";TIM$
780       WRT$ = "f0c2i" : CALL  IBWRT (BRD2%,WRT$)
785       J = 0
790       RECORD = 1
795   WHILE RECORD
800       CALL IBCLR (BRD1%)
805     WRT$ = "*N0.17E+2 P1F1R3T3?" : CALL IBWRT (BRD1%,WRT$)
810       MASK%= &H4800 : CALL IBWAIT (BRD1%,MASK%)
815       PRINT IBSTA%
820       RD$ = SPACE$(14) : CALL IBRD (BRD1%,RD$)
825       NUM = VAL(RD$)
830       PRINT NUM
835       TIM$ = TIME$
840       DAT$ = DATE$
845       J = J+1
850       IF J = 3  THEN  RECORD =0
851   WEND
852       NUM = NUM/10
853       PRINT #3,NUM;" volts ";"  ";DAT$;"   ";TIM$
854       WRT$ = "f5000000c2i" : CALL  IBWRT (BRD2%,WRT$)
855       PRINT MIN
860      MINA = VAL (MID$(TIME$,4,2))
865       SECA= VAL (MID$(TIME$,7,2))
870      DIFMIN =1
875   WHILE DIFMIN
880       IF ((MINA-PERIOD) = MIN )  THEN DIFMIN =0
885       IF (MINA+60-PERIOD) = MIN THEN DIFMIN = 0
895       MINA = VAL (MID$(TIME$,4,2))
900   WEND
905   DIFSEC = 1
910   WHILE DIFSEC
915       IF (SECA>SEC) OR (MINA>(MIN+5)) THEN  DIFSEC =0
920       SECA= VAL (MID$(TIME$,7,2))
925       MINA = VAL (MID$(TIME$,4,2))
930   WEND
935   RETURN
940   END
```

APPENDIX B

This appendix contains the source listing of the program GPREM2. This program is written in BASIC and is used in conjunction with a GPIB interface card to control the operation of a Fluke programmable multimeter. The multimeter and control program form the nucleus of a remote monitoring system.

```
1       CLEAR   ,59300!          ' BASIC Declarations
6       IBINIT1 = 59300!
11      IBINIT2 = IBINIT1 + 3    ' Lines 1 through 6 MUST be
        included in your program.
16      BLOAD "bib.m",IBINIT1
21      CALL IBINIT1(IBFIND,IBTRG,IBCLR,IBPCT,IBSIC,IBLOC,
        IBPPC,IBBNA,IBONL,IBRSC,IBSRE,IBRSV,IBPAD,IBSAD,
        IBIST,IBDMA,IBEOS,IBTMO,IBEOT,IBRDF,IBWRTF)
26      CALL IBINIT2(IBGTS,IBCAC,IBWAIT,IBPOKE,IBWRT,IBWRTA,
        IBCMD,IBCMDA,IBRD,IBRDA,IBSTOP,IBRPP,IBRSP,IBDIAG,
        IBXTRC,IBRDI,IBWRTI,IBRDIA,IBWRTIA,IBSTA%,
        IBERR%,IBCNT%)
31      REM Optionally include the following declarations
        in your program.
36      REM They provide appropriate mnemonics by which
41      REM to reference commonly used values.
        Some mnemonics (GET%, ERR%,
46      REM END%, ATN%) are preceded by "B"
        in order to distinguish
51      REM them from BASIC keywords.
56      REM
61      REM GPIB Commands
66      UNL% = &H3F      ' GPIB unlisten command
71      UNT% = &H5F      ' GPIB untalk command
76      GTL% = &H1       ' GPIB go to local
81      SDC% = &H4       ' GPIB selected device clear
86      BGET% = &H8      ' GPIB group execute trigger
91      TCT% = &H9       ' GPIB take control
96      LLO% = &H11      ' GPIB local lock out
101     DCL% = &H14      ' GPIB device clear
106     PPU% = &H15      ' GPIB ppoll unconfigure
111     SPE% = &H18      ' GPIB serial poll enable
116     SPD% = &H19      ' GPIB serial poll disable
121     PPE% = &H60      ' GPIB parallel poll enable
125     PPD% = &H70      ' GPIB parallel poll disable
131     REM
136     REM GPIB status bit vector
141     REM global variable IBSTA% and wait mask
146     BERR% = &H8000   ' Error detected
151     TIMO% = &H4000   ' Timeout
156     BEND% = &H2000   ' EOI or EOS detected
161     SRQI% = &H1000   ' SRQ detected by CIC
```

```
166     RQS% = &H800     ' Device needs service
171     CMPL% = &H100    ' I/O completed
176     LOK% = &H80      ' Local lockout state
181     REM% = &H40      ' Remote state

186      CIC% = &H20      ' Controller-In-Charge
191      BATN% = &H10     ' Attention asserted
196      TACS% = &H8      ' Talker active
201      LACS% = &H4      ' Listener active
206      DTAS% = &H2      ' Device trigger state
211      DCAS% = &H1      ' Device clear state
216      REM
221      REM Error messages returned in global variable
         IBERR%
226      EDVR% =  0       ' DOS error
231      ECIC% =  1       ' Function requires board to be CIC
236      ENOL% =  2       ' Write function detected no
         Listeners
241      EADR% =  3       ' Interface board not
                            addressed correctly
246      EARG% =  4       ' Invalid argument to function call
251      ESAC% =  5       ' Function requires board to be SAC
256      EABO% =  6       ' I/O operation aborted
261      ENEB% =  7       ' Non-existent interface board
266      EOIP% = 10       ' I/O operation started before
         previous operation completed
271      ECAP% = 11       ' No capability for operation
276      EFSO% = 12       ' File system operation error
281      EBUS% = 14       ' Command error during device call
286      ESTB% = 15       ' Serial poll status byte lost
291      ESRQ% = 16       ' SRQ remains asserted
296      REM
301      REM EOS mode bits
306      BIN% = &H1000    ' Eight bit compare
311      XEOS% = &H800    ' Send EOI with EOS byte
316      REOS% = &H400    ' Terminate read on EOS
321      REM
326      REM Timeout values and meanings
331      TNONE% =   0     ' Infinite timeout (disabled)
336      T10US% =   1     ' Timeout of 10 us (ideal)
341      T30US% =   2     ' Timeout of 30 us (ideal)
346      T100US% =  3     ' Timeout of 100 us (ideal)
351      T300US% =  4     ' Timeout of 300 us (ideal)
356      T1MS% =    5     ' Timeout of 1 ms (ideal)
361      T3MS% =    6     ' Timeout of 3 ms (ideal)
366      T10MS% =   7     ' Timeout of 10 ms (ideal)
371      T30MS% =   8     ' Timeout of 30 ms (ideal)
376      T100MS% =  9     ' Timeout of 100 ms (ideal)
381      T300MS% = 10     ' Timeout of 300 ms (ideal)
386      T1S% =    11     ' Timeout of 1 s (ideal)
391      T3S% =    12     ' Timeout of 3 s (ideal)
396      T10S% =   13     ' Timeout of 10 s (ideal)
```

```
401       T30S% =   14     ' Timeout of 30 s (idea
406       T100S% =  15     ' Timeout of 100 s (ideal)
411       T300S% =  16     ' Timeout of 300 s (ideal)
416       T1000S% = 17     ' Timeout of 1000 s (maximum)
421       REM
426       REM Miscellaneous
431       S% = &H8         ' Parallel Poll sense bit
436       LF% = &HA        ' Line feed character
441       REM
446       REM Application program variables passed to
451       REM GPIB functions
456       REM
461       CMD$ = SPACE$(10)        ' command buffer
466       RD$ = SPACE$(255)        ' read data buffer
471       WRT$ = SPACE$(255)       ' write data buffer
476       BNAME$ = SPACE$(7)       ' board name buffer
481       BDNAME$ = SPACE$(7)      ' board or device name buffer
486       FLNAME$ = SPACE$(50)     ' file name buffer
491       BDNAME$ = "gpib0"
496       CALL IBFIND (BDNAME$,BRD0%)
501       BDNAME$ = "flukemm"
506       CALL IBFIND (BDNAME$,BRD1%)
511       WRT$ = "rem"
516       V% = 13
521       CALL IBTMO (BRD1%,V%)
526       MEAS = 1
531       J = 1
536       MEAS = 1
541       FILE$ = "a:batdat.dat"
546       OPEN FILE$ FOR APPEND AS 3
551       FLE$ = "a:convert.dat"
556       OPEN FLE$ FOR APPEND AS 1
565       WHILE MEAS
575       CALL IBCLR (BRD1%)
585    WRT$ = "*N0.17E+2 P1F1R3T3?" : CALL IBWRT (BRD1%,WRT$)
595       MASK%= &H4800 : CALL IBWAIT (BRD1%,MASK%)
605       PRINT IBSTA%
615       RD$ = SPACE$(14) : CALL IBRD (BRD1%,RD$)
625       NUM = VAL(RD$)
626       ISREF = 0
627       ISDATA = 0
635       PRINT NUM
636       NOTREF = 1
637 WHILE NOTREF
638       IF (NUM >1.18) AND (NUM<1.21) THEN ISREF = 1 :
          REF = NUM : FIL= 3
639       IF (NUM > 9.899999) AND (NUM < 10.1) THEN ISREF= 1 :
          REF= NUM : FIL = 1
640     WRT$ = "*N0.17E+2 P1F1R3T3?" : CALL IBWRT (BRD1%,WRT$)
641       MASK%= &H4800 : CALL IBWAIT (BRD1%,MASK%)
642       PRINT IBSTA%
643       RD$ = SPACE$(14) : CALL IBRD (BRD1%,RD$)
```

```
644       NUM = VAL(RD$)
645       IF (NUM<>1.2) OR (NUM<>10) THEN ISDATA = 1
646       IF (ISDATA=1) AND (ISREF=1) THEN NOTREF=0
647 WEND
649       PRINT FIL
650       TIM$ = TIME$
660       DAT$ = DATE$
670       IF FIL =3 THEN PRINT #3,NUM; " VOLTS  " ;"   ";DAT$;"
          ";TIM$
671       IF FIL =1 THEN PRINT #1,NUM; " VOLTS  " ;"   ";DAT$;"
          ";TIM$
680       WEND
690 END
```

APPENDIX C

Test data for bidirectional link.

TEST DATA
BATDAT.DAT
Test commenced at time 09:30, with an applied voltage of .5106 V.
Sample interval set for 1 minute.

.00003	volts	12-31-1987	09:29:40
.64320	volts	12-31-1987	09:30:04
.52306	volts	12-31-1987	09:31:04
.52168	volts	12-31-1987	09:32:04
.52134	volts	12-31-1987	09:33:04
.52151	volts	12-31-1987	09:34:04
.51443	volts	12-31-1987	09:35:04
.51791	volts	12-31-1987	09:36:04
.52107	volts	12-31-1987	09:37:04
.52093	volts	12-31-1987	09:38:04
.52274	volts	12-31-1987	09:39:04
.52224	volts	12-31-1987	09:40:04
.52302	volts	12-31-1987	09:41:04
.53044	volts	12-31-1987	09:42:04
.53783	volts	12-31-1987	09:43:04
.53488	volts	12-31-1987	09:44:05
.53082	volts	12-31-1987	09:45:04
.52701	volts	12-31-1987	09:46:04
.52318	volts	12-31-1987	09:47:04
.52085	volts	12-31-1987	09:48:04
.52008	volts	12-31-1987	09:49:04
.52001	volts	12-31-1987	09:50:04
.52002	volts	12-31-1987	09:51:04
.51998	volts	12-31-1987	09:52:04
.51995	volts	12-31-1987	09:53:04
.5199	volts	12-31-1987	09:54:04
.51985	volts	12-31-1987	09:55:04

Average error for this segment +2.1%

Time 10:00 test voltage adjusted to .39602V.

.39521	volts	12-31-1987	10:00:37
.39498	volts	12-31-1987	10:01:04
.39486	volts	12-31-1987	10:02:04
.39472	volts	12-31-1987	10:03:04
.39453	volts	12-31-1987	10:04:04
.39441	volts	12-31-1987	10:05:04
.39435	volts	12-31-1987	10:06:04

.39428	volts	12-31-1987	10:07:04
.39424	volts	12-31-1987	10:08:04
.3942	volts	12-31-1987	10:09:04
.39413	volts	12-31-1987	10:10:04
.39411	volts	12-31-1987	10:11:04
.39411	volts	12-31-1987	10:12:04
.39406	volts	12-31-1987	10:13:04
.39402	volts	12-31-1987	10:14:04
.39398	volts	12-31-1987	10:15:04
.39396	volts	12-31-1987	10:16:04
.39394	volts	12-31-1987	10:17:04
.39397	volts	12-31-1987	10:18:04
.39398	volts	12-31-1987	10:19:04
.39398	volts	12-31-1987	10:20:04
.39395	volts	12-31-1987	10:21:04
.39392	volts	12-31-1987	10:22:04
.39389	volts	12-31-1987	10:23:04
.39384	volts	12-31-1987	10:24:04
.39381	volts	12-31-1987	10:25:04
.39381	volts	12-31-1987	10:26:04
.39381	volts	12-31-1987	10:27:04

Average error for this segment -.50% .

Time 10:27 test voltage changed to .301 V.

.39367	volts	12-31-1987	10:28:04
.2955	volts	12-31-1987	10:29:04
.29516	volts	12-31-1987	10:30:04
.29509	volts	12-31-1987	10:31:04
.29495	volts	12-31-1987	10:32:04
.29474	volts	12-31-1987	10:33:04
.29476	volts	12-31-1987	10:34:04
.29467	volts	12-31-1987	10:35:04
.29462	volts	12-31-1987	10:36:04
.29453	volts	12-31-1987	10:37:04
.2945	volts	12-31-1987	10:38:04
.29449	volts	12-31-1987	10:39:04
.29445	volts	12-31-1987	10:40:04
.29446	volts	12-31-1987	10:41:04
.29447	volts	12-31-1987	10:42:04
.2944	volts	12-31-1987	10:43:04
.29439	volts	12-31-1987	10:44:04
.29434	volts	12-31-1987	10:45:04
.29432	volts	12-31-1987	10:46:04
.29434	volts	12-31-1987	10:47:04
.29428	volts	12-31-1987	10:48:04
.29428	volts	12-31-1987	10:49:04
.29428	volts	12-31-1987	10:50:04
.29419	volts	12-31-1987	10:51:04
.29427	volts	12-31-1987	10:52:04

.29426	volts	12-31-1987	10:53:04
.29424	volts	12-31-1987	10:54:04
.29419	volts	12-31-1987	10:55:04

Average Error for this Section -2.3%

Time 10:55 test voltage adjusted to .206 V.

.19117	volts	12-31-1987	10:58:32
.19106	volts	12-31-1987	10:59:04
.19108	volts	12-31-1987	11:00:04
.19102	volts	12-31-1987	11:01:04
.19094	volts	12-31-1987	11:02:04
.19087	volts	12-31-1987	11:03:04
.19085	volts	12-31-1987	11:04:05
.19082	volts	12-31-1987	11:05:04
.19075	volts	12-31-1987	11:06:04
.19076	volts	12-31-1987	11:07:04
.19075	volts	12-31-1987	11:08:04
.19075	volts	12-31-1987	11:09:04
.19071	volts	12-31-1987	11:10:04
.19072	volts	12-31-1987	11:11:04
.19067	volts	12-31-1987	11:12:04
.19065	volts	12-31-1987	11:13:04
.19063	volts	12-31-1987	11:14:04
.19061	volts	12-31-1987	11:15:04
.1906	volts	12-31-1987	11:16:04
.19058	volts	12-31-1987	11:17:04
.19056	volts	12-31-1987	11:18:04
.19055	volts	12-31-1987	11:19:04
.19056	volts	12-31-1987	11:20:04
.19051	volts	12-31-1987	11:21:04
.19054	volts	12-31-1987	11:22:04
.19056	volts	12-31-1987	11:23:04
.19052	volts	12-31-1987	11:24:04
.19053	volts	12-31-1987	11:25:04
.19051	volts	12-31-1987	11:26:04
.19048	volts	12-31-1987	11:27:04
.19049	volts	12-31-1987	11:28:04
.19046	volts	12-31-1987	11:29:04
.1904	volts	12-31-1987	11:30:04

Average error for this section -7% .

Time 11:30 test voltage adjusted to .101 V.

.00018	volts	12-31-1987	11:31:04
.00018	volts	12-31-1987	11:32:04
.00019	volts	12-31-1987	11:33:04
.00019	volts	12-31-1987	11:34:04

.00019	volts	12-31-1987	11:35:04
.00018	volts	12-31-1987	11:36:04
.00019	volts	12-31-1987	11:37:04
.00019	volts	12-31-1987	11:38:04
.00019	volts	12-31-1987	11:39:04
.00019	volts	12-31-1987	11:40:04
.00019	volts	12-31-1987	11:41:04
.00019	volts	12-31-1987	11:42:05
.00019	volts	12-31-1987	11:43:04
.00019	volts	12-31-1987	11:44:04
.00019	volts	12-31-1987	11:45:04
.00019	volts	12-31-1987	11:46:04

.1 VOLT unreadable probable causes, non-linearities of LM331, prescaler amplifier misadjusted, and 80 ohm resistence of the multiplexer.

Time 11:45 adjusted test voltage to .145 V.

.13068	volts	12-31-1987	11:49:11
.13034	volts	12-31-1987	11:50:04
.1301	volts	12-31-1987	11:51:04
.12982	volts	12-31-1987	11:52:04
.12958	volts	12-31-1987	11:53:04
.12944	volts	12-31-1987	11:54:04
.12925	volts	12-31-1987	11:55:04
.12916	volts	12-31-1987	11:56:04
.12902	volts	12-31-1987	11:57:04
.12896	volts	12-31-1987	11:58:05

Average error for this section -11% .

Time 12:00 to 12:30 test delayed for system measurements.

.00019	volts	12-31-1987	12:00:16
.00019	volts	12-31-1987	12:01:04
.00019	volts	12-31-1987	12:02:04
.00019	volts	12-31-1987	12:03:04
.00019	volts	12-31-1987	12:04:04
.00019	volts	12-31-1987	12:05:04
.00019	volts	12-31-1987	12:06:04
.00019	volts	12-31-1987	12:07:04
.00021	volts	12-31-1987	12:08:04
.00019	volts	12-31-1987	12:09:04
.00019	volts	12-31-1987	12:10:04
.00018	volts	12-31-1987	12:11:04
.0002	volts	12-31-1987	12:12:05
.0002	volts	12-31-1987	12:13:04
.00019	volts	12-31-1987	12:14:04

.0126	volts	12-31-1987	12:15:05
.0126	volts	12-31-1987	12:16:05
.0126	volts	12-31-1987	12:17:05
.01259	volts	12-31-1987	12:18:05
.01259	volts	12-31-1987	12:19:05
.01258	volts	12-31-1987	12:20:05
.01259	volts	12-31-1987	12:21:05
.01258	volts	12-31-1987	12:22:05
.01258	volts	12-31-1987	12:23:05
.01258	volts	12-31-1987	12:24:05
.01257	volts	12-31-1987	12:25:06
.01258	volts	12-31-1987	12:26:05
.01257	volts	12-31-1987	12:27:05
.02165	volts	12-31-1987	12:28:05
-.00014	volts	12-31-1987	12:29:05
.10364	volts	12-31-1987	12:30:04
.10359	volts	12-31-1987	12:31:04
.10355	volts	12-31-1987	12:32:04
.10352	volts	12-31-1987	12:33:04
.1035	volts	12-31-1987	12:34:04

Time 12:35 sample interval adjusted to 59 minutes, test voltage adjusted to .5 V.

.1035	volts	12-31-1987	12:35:04
.5077	volts	12-31-1987	12:40:14
.5069	volts	12-31-1987	13:39:04
.50709	volts	12-31-1987	14:38:04
.50729	volts	12-31-1987	15:37:04

TEST COMPLETE

TEST DATA
CONVERT.DAT

Test commeced at 09:30, sample inerval adjusted to 1 minute, test voltage adjusted to 1.009 V.

.00005	volts	12-31-1987	09:29:37
1.05319	volts	12-31-1987	09:30:02
1.05134	volts	12-31-1987	09:31:02
1.05395	volts	12-31-1987	09:32:02
1.054	volts	12-31-1987	09:33:02
1.05414	volts	12-31-1987	09:34:02
1.05402	volts	12-31-1987	09:35:02
1.05408	volts	12-31-1987	09:36:02
1.05398	volts	12-31-1987	09:37:02
1.05398	volts	12-31-1987	09:38:02
1.05405	volts	12-31-1987	09:39:02
1.05404	volts	12-31-1987	09:40:02
1.0534	volts	12-31-1987	09:41:02
1.05398	volts	12-31-1987	09:42:02
1.0539	volts	12-31-1987	09:43:02
1.05389	volts	12-31-1987	09:44:02
1.05392	volts	12-31-1987	09:45:02
1.05392	volts	12-31-1987	09:46:02
1.05382	volts	12-31-1987	09:47:02
1.05391	volts	12-31-1987	09:48:02
1.05387	volts	12-31-1987	09:49:02
1.05385	volts	12-31-1987	09:50:02
1.05379	volts	12-31-1987	09:51:02
1.0538	volts	12-31-1987	09:52:02
1.05373	volts	12-31-1987	09:53:02
1.05364	volts	12-31-1987	09:54:02
1.05364	volts	12-31-1987	09:55:02

Average error for this section + 5%.

Time 10:00 test voltage adjusted to .9086 V.

.94607	volts	12-31-1987	10:00:35
.94631	volts	12-31-1987	10:01:02
.94609	volts	12-31-1987	10:02:02
.94596	volts	12-31-1987	10:03:02
.94587	volts	12-31-1987	10:04:02
.94582	volts	12-31-1987	10:05:02
.94579	volts	12-31-1987	10:06:02
.94567	volts	12-31-1987	10:07:02
.94557	volts	12-31-1987	10:08:02
.94556	volts	12-31-1987	10:09:02
.94546	volts	12-31-1987	10:10:02
.94539	volts	12-31-1987	10:11:02

.94547	volts	12-31-1987	10:12:02
.94538	volts	12-31-1987	10:13:02
.94529	volts	12-31-1987	10:14:02
.94524	volts	12-31-1987	10:15:02
.94519	volts	12-31-1987	10:16:02
.94519	volts	12-31-1987	10:17:02
.945189	volts	12-31-1987	10:18:02
.94511	volts	12-31-1987	10:19:02
.94509	volts	12-31-1987	10:20:02
.94508	volts	12-31-1987	10:21:02
.94502	volts	12-31-1987	10:22:02
.94506	volts	12-31-1987	10:23:02
.94496	volts	12-31-1987	10:24:02
.94492	volts	12-31-1987	10:25:02
.94490	volts	12-31-1987	10:26:02
.94495	volts	12-31-1987	10:27:02

Average error for this section +4% .

Test voltage adjusted to .7888 V.

.78507	volts	12-31-1987	10:28:02
.81858	volts	12-31-1987	10:29:02
.81832	volts	12-31-1987	10:30:02
.81824	volts	12-31-1987	10:31:02
.81811	volts	12-31-1987	10:32:02
.81805	volts	12-31-1987	10:33:02
.81792	volts	12-31-1987	10:34:02
.81786	volts	12-31-1987	10:35:02
.81785	volts	12-31-1987	10:36:02
.81777	volts	12-31-1987	10:37:02
.81772	volts	12-31-1987	10:38:02
.817730	volts	12-31-1987	10:39:02
.81762	volts	12-31-1987	10:40:02
.81768	volts	12-31-1987	10:41:02
.81767	volts	12-31-1987	10:42:02
.81771	volts	12-31-1987	10:43:02
.81759	volts	12-31-1987	10:44:02
.81753	volts	12-31-1987	10:45:02
.81753	volts	12-31-1987	10:46:02
.81756	volts	12-31-1987	10:47:02
.81744	volts	12-31-1987	10:48:02
.81745	volts	12-31-1987	10:49:02
.81723	volts	12-31-1987	10:50:02
.81715	volts	12-31-1987	10:51:02
.8172	volts	12-31-1987	10:52:02
.8172	volts	12-31-1987	10:53:02
.81715	volts	12-31-1987	10:54:02
.81714	volts	12-31-1987	10:55:02

Average error for this section +3.6% .

Test voltage adjusted to .694 V.

.71623	volts	12-31-1987	10:58:30
.71649	volts	12-31-1987	10:59:02
.71632	volts	12-31-1987	11:00:02
.71617	volts	12-31-1987	11:01:02
.71605	volts	12-31-1987	11:02:02
.716	volts	12-31-1987	11:03:02
.71592	volts	12-31-1987	11:04:02
.71586	volts	12-31-1987	11:05:02
.71577	volts	12-31-1987	11:06:02
.71574	volts	12-31-1987	11:07:02
.71563	volts	12-31-1987	11:08:02
.71561	volts	12-31-1987	11:09:02
.71558	volts	12-31-1987	11:10:02
.71559	volts	12-31-1987	11:11:02
.71555	volts	12-31-1987	11:12:02
.7156	volts	12-31-1987	11:13:02
.71563	volts	12-31-1987	11:14:02
.71548	volts	12-31-1987	11:15:02
.71545	volts	12-31-1987	11:16:02
.71545	volts	12-31-1987	11:17:02
.71543	volts	12-31-1987	11:18:02
.71548	volts	12-31-1987	11:19:02
.7154	volts	12-31-1987	11:20:02
.71534	volts	12-31-1987	11:21:02
.7153	volts	12-31-1987	11:22:02
.71534	volts	12-31-1987	11:23:02
.71531	volts	12-31-1987	11:24:02
.71532	volts	12-31-1987	11:25:02
.71531	volts	12-31-1987	11:26:02
.71528	volts	12-31-1987	11:27:02
.71531	volts	12-31-1987	11:28:02
.71528	volts	12-31-1987	11:29:02
.71527	volts	12-31-1987	11:30:02

Average error for this sectiion +3% .

Test voltage adjusted to .587 V.

.60379	volts	12-31-1987	11:31:02
.60331	volts	12-31-1987	11:32:02
.60299	volts	12-31-1987	11:33:02
.60272	volts	12-31-1987	11:34:02
.60247	volts	12-31-1987	11:35:02
.60234	volts	12-31-1987	11:36:02
.60223	volts	12-31-1987	11:37:02
.60211	volts	12-31-1987	11:38:02
.60204	volts	12-31-1987	11:39:02

.60197	volts	12-31-1987	11:40:02
.60187	volts	12-31-1987	11:41:02
.60174	volts	12-31-1987	11:42:02
.60171	volts	12-31-1987	11:43:02
.60163	volts	12-31-1987	11:44:02
.60157	volts	12-31-1987	11:45:02
.60155	volts	12-31-1987	11:46:02
.61724	volts	12-31-1987	11:49:09
.61742	volts	12-31-1987	11:50:02
.61737	volts	12-31-1987	11:51:02
.61728	volts	12-31-1987	11:52:02
.61721	volts	12-31-1987	11:53:02
.61718	volts	12-31-1987	11:54:02
.61714	volts	12-31-1987	11:55:02
.61712	volts	12-31-1987	11:56:02
.61704	volts	12-31-1987	11:57:02
.617	volts	12-31-1987	11:58:02
.61651	volts	12-31-1987	12:00:13
.61632	volts	12-31-1987	12:01:02
.6167	volts	12-31-1987	12:02:02
.61673	volts	12-31-1987	12:03:02
.61676	volts	12-31-1987	12:04:02
.6167	volts	12-31-1987	12:05:02
.61666	volts	12-31-1987	12:06:02
.61666	volts	12-31-1987	12:07:02
.61667	volts	12-31-1987	12:08:02
.61661	volts	12-31-1987	12:09:02
.6166	volts	12-31-1987	12:10:02
.61656	volts	12-31-1987	12:11:02
.61659	volts	12-31-1987	12:12:02
.61658	volts	12-31-1987	12:13:02
.61655	volts	12-31-1987	12:14:02

Average error for this section +4% .

Test interupted for system measurements.

.05978	volts	12-31-1987	12:15:02
.05978	volts	12-31-1987	12:16:02
.05978	volts	12-31-1987	12:17:02
.05978	volts	12-31-1987	12:18:02
.05978	volts	12-31-1987	12:19:02
.05977	volts	12-31-1987	12:20:02
.05977	volts	12-31-1987	12:21:02
.05977	volts	12-31-1987	12:22:02
.05977	volts	12-31-1987	12:23:02
.05977	volts	12-31-1987	12:24:02
.05977	volts	12-31-1987	12:25:02
.05978	volts	12-31-1987	12:26:02
.05978	volts	12-31-1987	12:27:02

.05978	volts	12-31-1987	12:28:02
-.00018	volts	12-31-1987	12:29:03
.57832	volts	12-31-1987	12:30:02
.57829	volts	12-31-1987	12:31:02
.57828	volts	12-31-1987	12:32:02
.57824	volts	12-31-1987	12:33:02
.57822	volts	12-31-1987	12:34:02
.5782	volts	12-31-1987	12:35:02

Test resumed time 12:39, sample interval
59 minutes, test voltage .9617 V.

.99972	volts	12-31-1987	12:40:12
.99898	volts	12-31-1987	13:39:02
.99908	volts	12-31-1987	14:38:02
.999269	volts	12-31-1987	15:37:02

Test cmpleted

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